Digitized by the Internet Archive
in 2022 with funding from
Boston Public Library

https://archive.org/details/passivesolarjour00inte_0

Passive
Solar
Journal

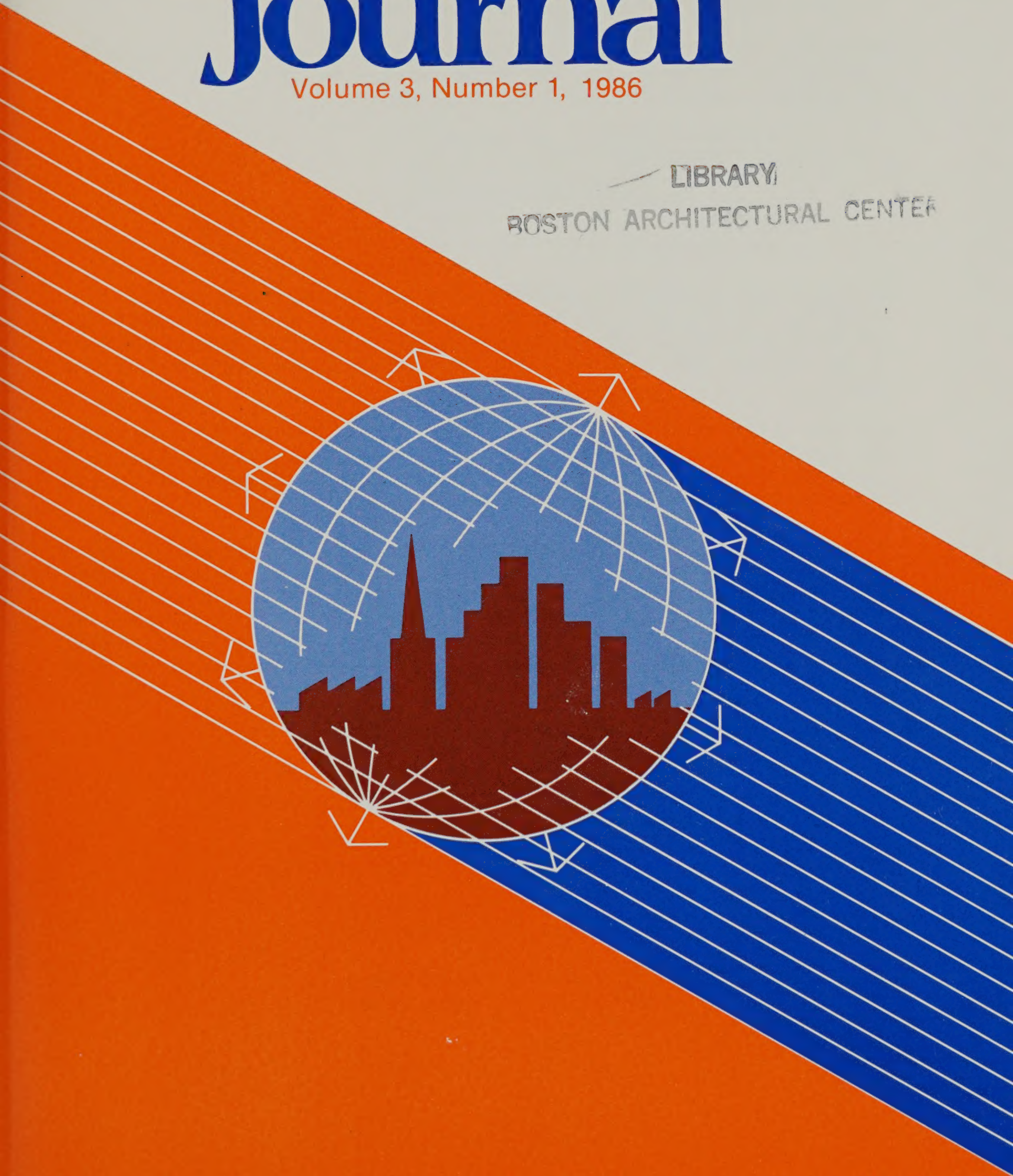
[illegible]

0277-6456

Passive Solar Journal

Volume 3, Number 1, 1986

LIBRARY
BOSTON ARCHITECTURAL CENTER



Heating, Cooling, and Lighting for Buildings

PASSIVE SOLAR JOURNAL

Sponsorship. *Passive Solar Journal* is the official journal of the Passive Architecture and Construction Division of the American Solar Energy Society, Inc.

Indexing and Abstracting Services. Articles published in *Passive Solar Journal* selectively appear in all major indexing and abstracting publications.

Manuscript Preparation and Submission. See inside back cover.

Subscription Information. *Passive Solar Journal* (ISSN: 0277-6456) is published in four numbers by Marcel Dekker, Inc., 270 Madison Avenue, New York, New York 10016. The subscription rate for Volume 3 (1986), is as follows:

Non-Member Institutions	$ 125.00
Society Member Institutions	90.00
ASES Membership Dues	150.00
Non-Member Individuals	47.50
Society Member Individuals	25.00
ASES Membership Dues	50.00

Your order must be prepaid by personal check or may be charged to MasterCard, VISA, or American Express. Please add $12.00 for surface postage outside the United States. For airmail to Europe, add $15.00; to Asia, add $19.00. Please mail payment with order to: Marcel Dekker, Inc., P. O. Box 11305, Church Street Station, New York, New York 10249.

Copyright © 1986 by Marcel Dekker, Inc. All rights reserved. Neither this work nor any part may be reproduced or transmitted in any form or by any means, electronic or mechanical, microfilming and recording, or by any information storage and retrieval systems without permission in writing from the publisher.

Authorization to photocopy items for internal or personal use, or the internal or personal use of specific clients, is granted by Marcel Dekker, Inc. for users registered with the Copyright Clearance Center (CCC) Transactional Reporting Service, provided that the base fee of $3.50 per copy is paid directly to CCC, 27 Congress Street, Salem, MA 01970. For those organizations that have been granted a photocopy license by CCC, a separate system of payment has been arranged. The fee code for users of the Transactional Reporting Service is: 0277-6456/86$3.50.

Contributions to this journal are published free of charge.

Passive Solar Journal

Official Journal of the Passive Architecture
and Construction Division of the
American Solar Energy Society, Inc.

Editor-in-Chief

ROBERT W. JONES
Los Alamos National Laboratory
Mail Stop J577
Los Alamos, New Mexico 87545

Assistant Editor

MELANIE BLAIN
Los Alamos National Laboratory

Production Editor

NANCY S. REECE
Solar Energy Research Institute
1617 Cole Boulevard
Golden, Colorado 80401

Consulting Editor

JEFFREY COOK
Arizona State University

Associate Editors

DENNIS A. ANDREJKO
State University of New York

J. DOUGLAS BALCOMB
Los Alamos National Laboratory

SUBRATO CHANDRA
Florida Solar Energy Center

EUGENE CLARK
Trinity University

JOHN W. HAYES
Marlboro College

MICHAEL J. HOLTZ
Architectural Energy Corp.

BRUCE D. HUNN
University of Texas

DONALD A. NEEPER
Los Alamos National Laboratory

CLAUDE ROBBINS
Solar Energy Research Institute

RICK SCHWOLSKY
Grafton Builders

ROBERT O. SMITH
Robert O. Smith & Associates

AIMS AND SCOPE

The **Passive Solar Journal** is the official journal of the Passive Architecture and Construction Division of the American Solar Energy Society, Inc., the United States Section of the International Solar Energy Society. This organization has sponsored major national and international passive conferences. The **Journal** is guided by a distinguished editorial board, an international panel of advisors, and expert peer reviewers.

The purpose of the **Passive Solar Journal** is to stimulate and support the flow and exchange of research and professional information. The **Journal** is intended to become the archival record and the standard international reference for the field, with principal directions and issues documented in illustrated and referenced presentations. Annual indexes provide detailed cross-reference access. The **Journal** contains full-length articles, book reviews, and opinions that meet the highest standards of verbal and graphic communication. The scope of subject matter is passive solar heating, passive cooling, and natural lighting plus related subjects including the following:

Advanced concepts
Building climatology
Codes and standards
Community planning
Component design
Computer methods
Conservation
Construction details
Control systems
Daylighting
Design tools
Direct gain
Domestic hot water
Earth coupling
Economic analysis
Education
Energy budgets
Energy storage
Evaporative cooling
Historical examples
Hybrid systems
Indirect gain
Indoor air quality
Instrumentation
Integration and optimization
Landscaping
Lifestyles and needs
Market development
Movable insulation
Phase change materials
Photovoltaic interface
Radiation resources
Retrofits
Roof ponds
Selective surfaces
Shading
Simulation
Sky radiation
Solar architecture
Solar greenhouses
Sunspaces
Testing and monitoring
Thermal comfort
Thermal networks
Thermosiphons
Trombe walls
Underground climate
Urban design
User evaluation
Ventilation
Window systems

Passive Solar Journal

Volume 3, Number 1, 1986

Contents

Editorial 1
P. McFadden and R. Jones

Evaporative Cooling in Phoenix: Direct and Two-Stage Systems Compared with a Heat Pump 3
J. Cook

Natural Convection Research and Solar Building Applications 33
R. Anderson

Solar Load Ratio Design Tool Predictions Compared to Level B Monitoring Data 77
J. Duffy and D. Odegard

Opinion/Passive Solar Sunset: Predicting Our Own Demise 99
M. Milne

Book Review/Daylight in Architecture by Benjamin Evans 105
M. Millet

About the Contributors 113

Passive Solar Journal, 3(1) 1 (1986)

Editorial

Welcome to the new **Passive Solar Journal.** As you can see, we have a new editor, publisher, and format. In addition, the Passive Systems Division and the Architecture and Construction Division have merged to form the Passive Architecture and Construction (PAC) Division. The **Passive Solar Journal** was formerly the official journal of the Passive Systems Division; now it is the official journal of the combined PAC Division. Accordingly, the scope of the **Journal** will be broadened to encompass the interests of this enlarged group. Despite these changes, the aims of the **Journal** are the same--to serve passive solar professionals with the highest quality information available.

Because the **Journal** is the principal means of communication among professionals in the solar buildings community, we see it as a crucial element of the PAC Division and ASES. Solar buildings are an important part of a rational energy alternative, and we aim to present exemplary solutions that promote attractive, comfortable, economical, and energy-efficient buildings. We encourage your participation in this communication process. We need your readership, your critical comments, and especially your contributions of articles, book reviews, and opinions.

We are committed to timely and regular publication. The **Journal** is a quarterly, so you can expect four issues for each year's subscription. Because the decision to restart the **Journal** was recent, this year's publication schedule is compressed, but you can expect the three other 1986 issues by the end of the year. Thank you for your continued support.

Pamm McFadden

Pamm McFadden
Chair
Passive Architecture and
Construction Division

RW Jones

Robert W. Jones
Editor-in-Chief
Passive Solar Journal

Passive Solar Journal, 3(1), 3-31 (1986)

Evaporative Cooling in Phoenix: Direct and Two-Stage Systems Compared with a Heat Pump

Jeffrey Cook
School of Architecture
Arizona State University
Tempe, Arizona 85287

Abstract

The design, construction, and performance of three similar townhouses in Phoenix, Arizona, are described. All have similar passive hybrid heating using a two-story sunspace coupled with a fan-forced duct system. However, each has a different cooling system: the west unit has a heat pump; the center unit, a direct evaporative cooler; and the east unit, a two-stage evaporative cooling system using a rock bed for thermal storage of nighttime-generated coolness. In addition, occupant behavior and thermal loads were not identical. The townhouses were completed in January 1983 and have been occupied continuously thereafter.

Copyright © 1986 by Marcel Dekker, Inc.

Monthly electricity charges for the summer of 1983 demonstrate major differences in the operating costs of these systems that confirm calculated predictions for comfort in a demanding desert climate. In August 1983, for example, the most demanding summer month, the average daily cost of residential space cooling by heat pump is $2.78, by direct evaporative cooler is $1.13, and by two-stage evaporative cooling system is $0.71, a typical comparative pattern. Because of the many other uncontrollable factors affecting performance, these results are approximate. Capital costs, comfort, and convenience are not accounted for. Thus, in general, in a hot desert climate such as Phoenix, a two-stage evaporative system can provide comparable comfort for one-third the operating cost of a refrigerated or heat pump system.

INTRODUCTION

Three similar, attached, two-story townhouses in Phoenix, each with a different cooling system, offer a unique opportunity for comparison. By reading the electric meters and reviewing actual monthly electric bills, we compared the running costs of the two most common cooling systems with an innovative two-stage evaporative cooling system that uses a rock bed. A study of the 1983 summer electric bills for the cooling systems demonstrates their success as economical heating/cooling systems for residences in this climate.

CLIMATE

The low desert climate of Phoenix, Arizona, (latitude 33 degrees north) is characterized by mild winters and hot summers. Swing seasons of spring and fall are relatively short and offer no additional thermal problems. High standards of insulation and cross-ventilation are appropriate tempering strategies for all seasons. Passive solar heating in winter can be readily employed in this climate, but designs should not cause unwanted heat gain in summer. The five months of summer and accompanying overheating problems represent a challenge to passive space conditioning.

The hot Phoenix summers are both long and intense. They are characterized by two distinct phases: a very hot and dry period is punctuated during part of July and all of August by the "monsoon" or humid season. Since the ambient air temperatures are the highest and most persistent urban temperatures in the United States, they test American cooling technologies. Compression refrigeration is recognized as the most dependable technique under such conditions. However, because of high operating costs and the costs of maintaining and replacing compressors, less sophisticated cooling techniques such as passive and hybrid cooling methods are becoming popular. The most developed hybrid cooling system for arid regions is evaporative cooling. Including the costs of evaporating water and running the fan motor, evaporative coolers typically operate for about one quarter the cost of compression refrigeration (Cook, 1979).

The evaporative cooler was commercialized in Phoenix during the 1930s. Although Phoenix is the world manufacturing center for evaporative cooling equipment, its climate defies such equipment: comfort is possible only during the spring and fall. A combination of high air temperatures and high relative humidities during the monsoon has earned single-stage evaporative coolers the accolade of "swamp coolers."

PROGRAM

Sunspace is an innovative, energy-conscious design built in the low desert climate of Phoenix, Arizona, at an elevation of 1266 ft (386 m) above mean sea level. The building (Figure 1) is at the corner of North 15th Avenue and Cochise Drive, two blocks south of Peoria Avenue. Construction was begun in March 1982 and completed in January 1983. The design was the only prize winner in the multifamily category of the Arizona Passive Solar Design Competition held in 1981 (Arizona Solar Energy Commission, 1981). The jurors made numerous compliments about the design: "straightforward to build, simple in design and a compact, tight building"; "a well arranged structure"; ". . . exhibits an interesting use of the rock bed, two-stage evaporative cooling system . . . it has a great deal of merit for its classification." The unique passive/hybrid design of the cooling system based on rock bed thermal storage has been published both nationally (Cook, 1983a) and abroad (Cook, 1983b).

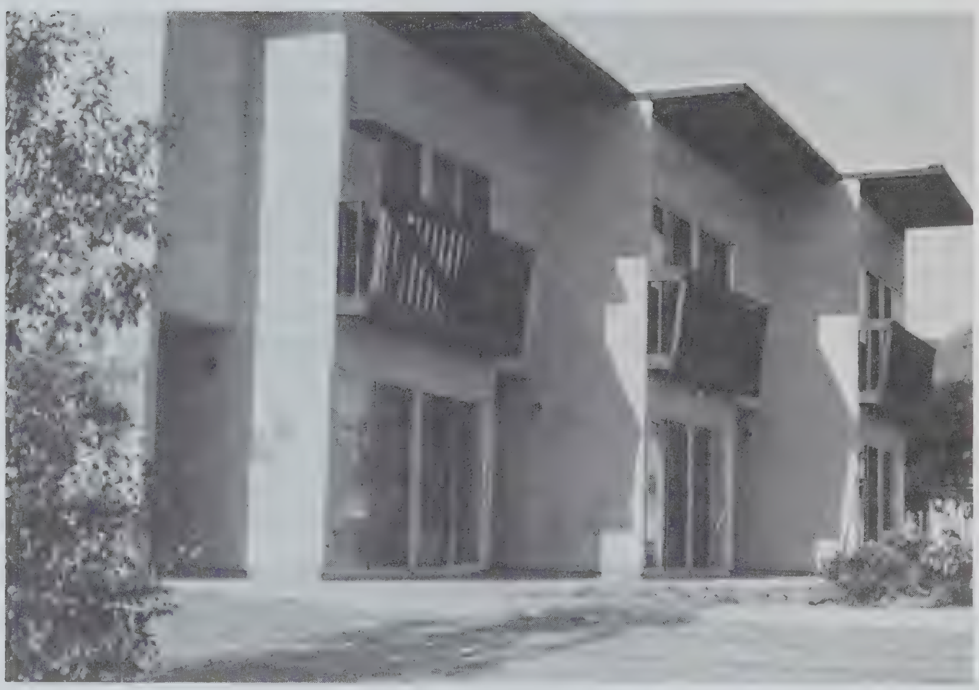


Figure 1. Sunspace units from the southwest. Three similar side-by-side townhouses each with a different cooling system provide an ideal comparison for operating costs. None of the passive/hybrid cooling or heating features is obvious on the exterior.

Designed, constructed, and owned by a group of five energy-conscious investors, these housing units were intended to be sold as condominiums. As a result, the designs incorporate standards of space, amenity, and operation appropriate to homeowners although the units are currently occupied by renters. The two-bedroom design was intended to fill a need for quality multifamily housing in northwest Phoenix, particularly for young professional couples. Alternatively, the design is suitable for retirees or those living on fixed incomes. For these users, solid construction, good insulation, and low operating costs are critical, especially considering utility rate increases and inflated housing costs.

PLAN

The principal feature of the site planning is the orientation of the apartments 12 degrees east of south. This orientation favors winter morning heating by the sun through the sunspaces. In summer, however, this orientation reduces solar heat gain when the hot afternoon sun would hit blank west faces.

Each housing unit is 1150 ft^2 (107 m^2) (Figure 2). Major entries on both the north and south sides allow flexible access. The built-in kitchen includes a sink, a garbage disposal, an electric range, and a 15.5 ft^3 (0.46 m^3) refrigerator. A half bath (lavatory and water closet) near the north door also accommodates a washing machine or combination washer-dryer. A breakfast bar, dining space, and the living area constitute a continuous open space on the ground floor that faces a two-story greenhouse/sunspace.

The sunspace has a finished floor and can be used as an additional social space although it is intended for potted plants and as part of the passive heating and cooling system. The open stairs are opposite the south entrance and could be separated by a partition from the living area.

A technical feature of the plan is the mechanical tower on the northwest corner of each apartment. The solar hot water tank, evaporative coolers, space refrigeration units, and mechanically operated dampers are accessible only from outdoors, thus separating heat, noise, moisture, and maintenance related to these systems from the interior (Figures 3 and 4).

SERVICES

The City of Phoenix provides water and sewer connections with a single water meter for all apartments and an underground watering system for irrigating the landscaping. No flood irrigation is available because the land is higher than the nearest canal; the Arizona Canal is to the south.

Arizona Public Service (APS) provides electricity. The electrical rate applicable to all three units is EC-1.

Each apartment has a solar domestic water heater consisting of two 20 ft^2 (1.9 m^2) collectors of the ASU Workshop design mounted at a 50 degree tilt on the roof. These collectors supply an 82-gal (310 l) solar tank located in a closet on the second story and accessible from the outside. Electric resistance provides backup.

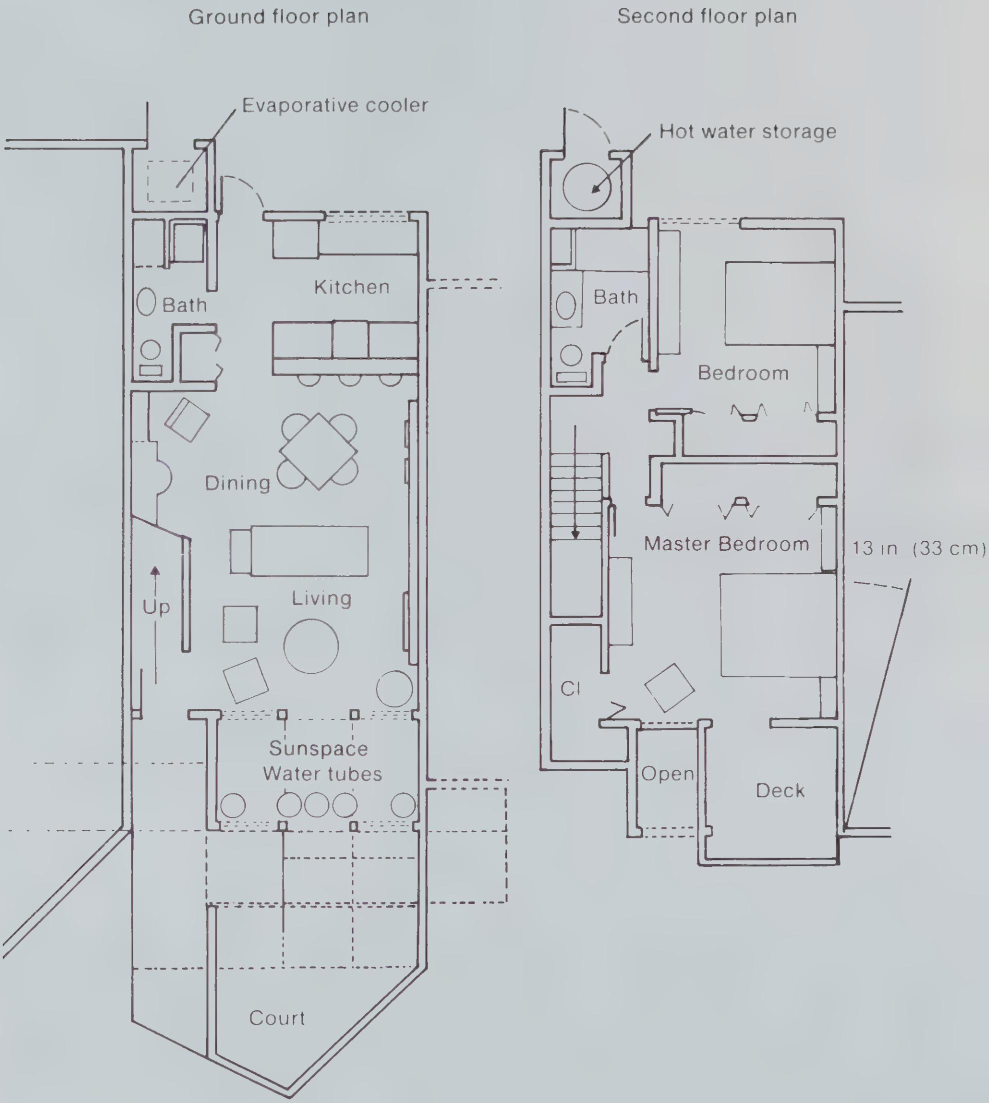


Figure 2. Ground floor and second floor plan

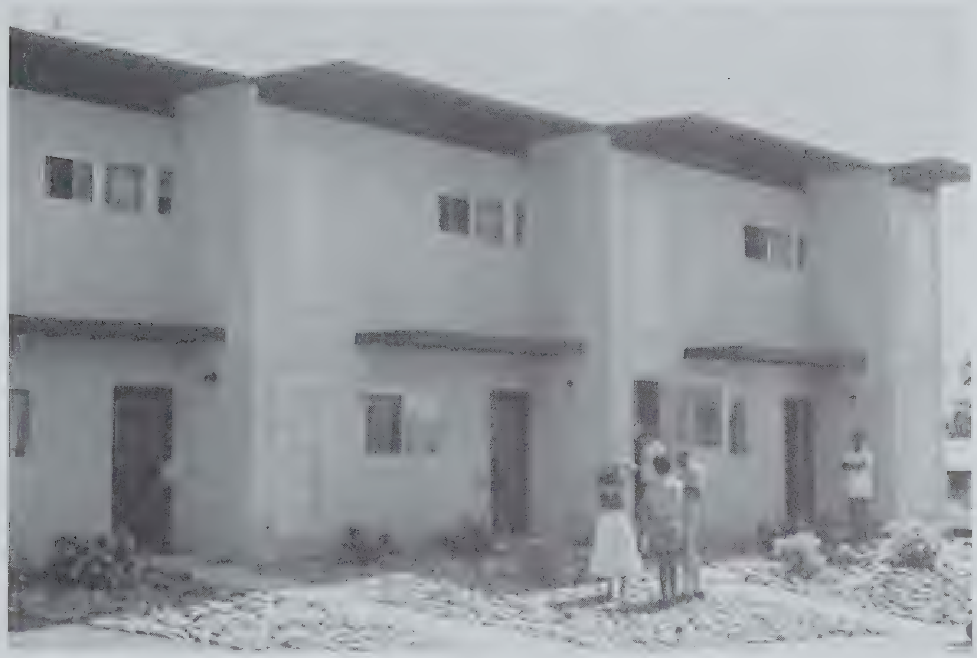


Figure 3. Sunspace townhouses from the northeast. The north (kitchen) sides also have a two-story service closet accessible only from the outside. The two access doors are barely visible. The closet contains the solar hot water storage tank as well as the respective cooling systems: evaporative coolers or heat pump coil unit.

ENERGY FEATURES

The two-story design with common east and west walls is itself an energy-conserving geometry for buildings in any climate. Extensive insulation of the wood frame, selective shading, and multiple glazings are also critical to the construction.

The roof is the largest surface area exposed to the sun. By using 16 in. (40 cm) prefabricated flat trusses of wood, a minimum insulation of R-40 (RSI 6.9) (blown cellulose) has an air space above that is naturally vented through a continuous soffit lattice. The plywood roof deck is waterproofed by a vinyl membrane with reflective aluminum (type 754).

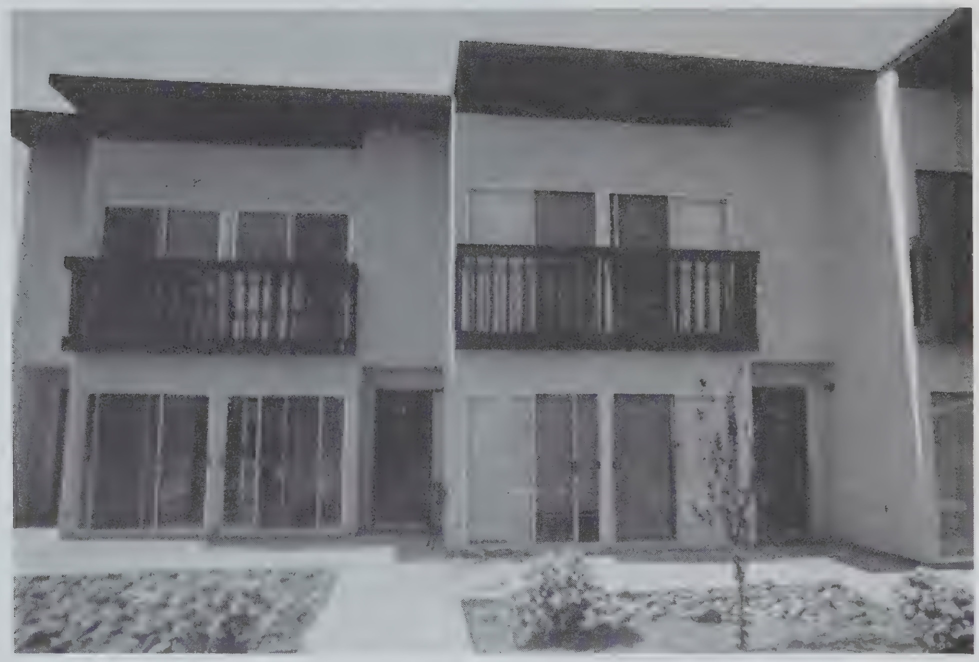


Figure 4. South elevation of two Sunspace units. The principal feature of the south side of each townhouse is a two-story sunspace that can be used as a greenhouse, or an extension of the living room on the ground floor and a discrete balcony for the master bedroom upstairs.

The exterior walls have 2 x 6 in. (5 x 15 cm) studs at 24 in. (60 cm) spacing with Kraft-faced fiberglass batts and stucco over a 1 in. (2.5 cm) polystyrene sheathing. The insulation rating is approximately R-24 (RSI 4.2). The common walls between units are double framed with 2 x 4 in. (5 x 10 cm) studs and R-13 (RSI 2.4) fiberglass batts in each wall. This construction isolates each unit structurally, thermally, and acoustically. The thermal separation permits the occupants of each unit to maintain their own temperature control. The foundation walls are insulated with 2 in. (5 cm) of polystyrene to isolate the rock beds for thermal storage.

All patio doors are tempered glass. Windows and interior patio doors into the sunspace from the interior are double glazed. The exterior glazing of the sunspace is single glazed; Venetian blinds control light and privacy.

The floor slabs on the main floors are 3.5 in. (8.9 cm) reinforced concrete on 2 in. (5 cm) polystyrene foam. The kitchen floors are 2 x 12 in. (5 x 30 cm) joist frame at 16 in. (40 cm) construction, insulated with R-19 (RSI 3.3) batts to provide a resilient walking surface. The structural floor systems at the ground level are heated and cooled by the rock beds and plenums underneath to provide a radiant comfort source for the interior.

The second floors are framed with 2 x 12 in. (5 x 30 cm) floor joists at 16 in. (41 cm). Walls and ceilings are finished with 1/2 in. (1.2 cm) drywall plasterboard. Water-resistant "green board" is used in the bathrooms and laundries.

Special attention was paid in design and construction to the structural issues of uplift, shear, and racking. Complete vapor barriers are used throughout.

There are no windows on the east or west walls. Operable windows face both north and south on both floors allowing good cross-ventilation. The two-story sunspace can act as a thermal chimney: cooler air is pulled into the north side of the house and exhausted out of the top of the south-facing sunspace from the natural convection created in a solar-heated area.

A deep overhang shades the south side in summer while permitting the lower angled winter sunlight to heat the solar greenhouse. Upper story Venetian blinds allow privacy and selective solar control. Exterior roll-down shades for the south-facing glass in the lower story have not been installed although the sunspace balcony provides some fixed shading in the summer (Figures 5 and 6).

North windows are shaded by the shape of the building except for short daily periods near sunrise and sunset around the summer solstice.

THERMAL STORAGE

Adequate thermal storage assures comforable indoor conditions regardless of the variations of desert climate outdoors. Both summer and winter days in Phoenix have high diurnal temperature

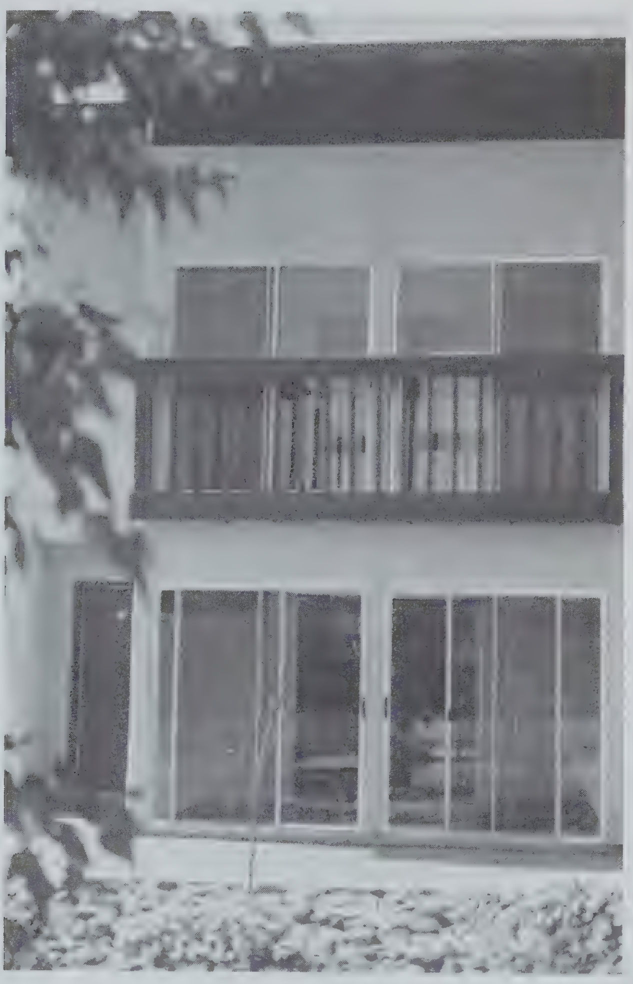


Figure 5. South elevation of Sunspace townhouse. Although deep overhangs protect the upper solar windows, the exterior roll-down shades to protect the lower sun-facing glass had not been installed during the summer when comparative cooling costs were studied.

swings; the difference between daytime high and nighttime low is usually between 40° and 50°F (22° and 28°C). Thus thermal storage is an important strategy for thermal stability.

Aside from the thermal storage qualities of typical furnishings and the drywall plasterboard on the walls and ceilings, three special thermal storage strategies stand out:

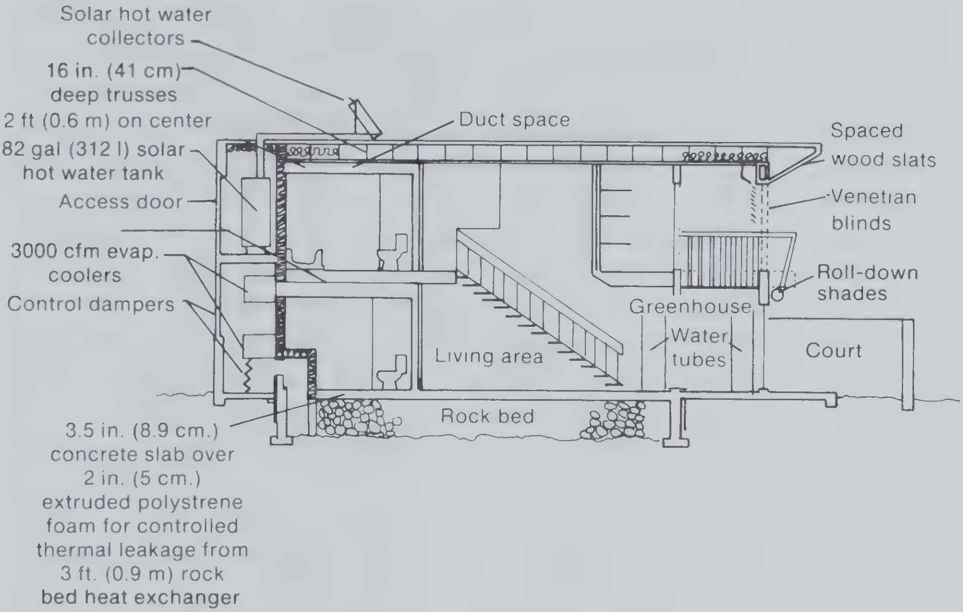

Solar hot water collectors
16 in. (41 cm) deep trusses 2 ft (0.6 m) on center
82 gal (312 l) solar hot water tank
Access door
3000 cfm evap. coolers
Control dampers
3.5 in. (8.9 cm.) concrete slab over 2 in. (5 cm.) extruded polystrene foam for controlled thermal leakage from 3 ft. (0.9 m) rock bed heat exchanger
Duct space
Spaced wood slats
Venetian blinds
Roll-down shades
Greenhouse
Water tubes
Court
Living area
Rock bed

Figure 6. Section

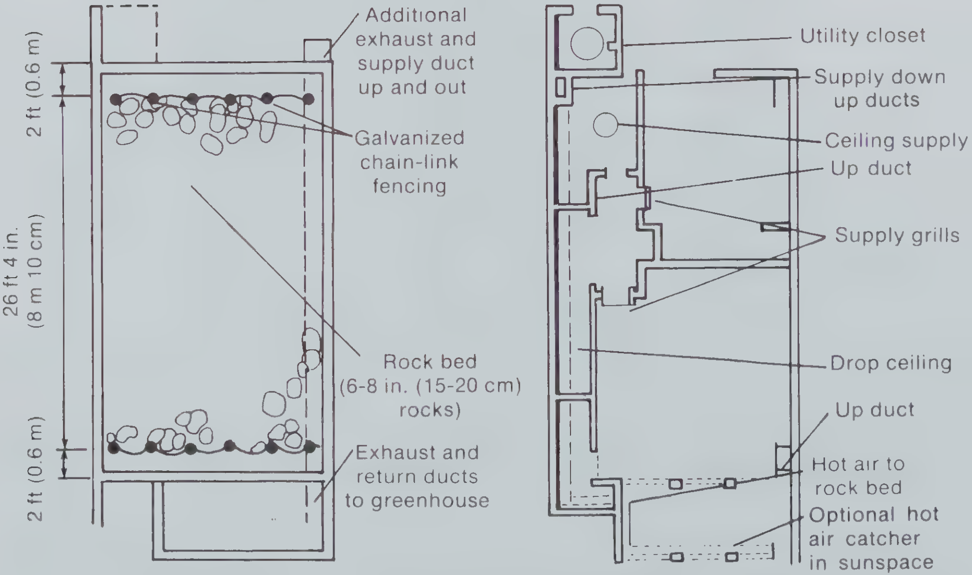
- The concrete slab on the main floor of the sunspace has been colored so that it can serve as an exposed finish surface. An occasional scatter rug would not significantly reduce its effectiveness. But wall-to-wall carpeting on the ground floor slab in the living and dining space reduces the heat transfer effectiveness of the slab.

- Exposed plastic tubes filled with water have yet to be installed. These tubes were to be placed near the south-facing windows in the living room and in the sunspace where they would diffuse direct sunlight and absorb heat to stabilize temperature fluctuations generated by solar direct gain.

- Underfloor rock beds have been constructed under all three housing units. They can be used in summer and winter for both cooling and heating. [Innovative design and construction of the rock beds have been reported (Cook 1983a and b).] The rocks are heated or cooled by forcing air horizontally through the

> rock bed. The charged rock bed is discharged in a similar way: by mechanically blowing air through the rock bed, or by unassisted vertical heat transfer such as convection or radiation. Radiation through the concrete slab floor directly on top passively conditions spaces on the ground floor over an extended period.

The rock beds are the full width of each unit, 17 ft 0 in. (5.2 m) (Figure 7). The depth of the rock bed is variable [approximately 4 ft 6 in. (1.4 m) deep] as determined by heat gain/loss calculations to accommodate the maximum 24-hour cooling need. The distance the air passes through the rock bed is approximately 23 ft 0 in. (6.9 m). The size of the rocks in this design, 4-8 in. (10-20 cm), is scaled by the dimensions of a diurnal thermal pulse with a fixed flow rate provided by a mechanical blower system. An open crawl space at each end of the rock bed serves as access for inspection and maintenance as well as an air plenum for distribution and collection.


2 ft (0.6 m)
26 ft 4 in. (8 m 10 cm)
2 ft (0.6 m)
Additional exhaust and supply duct up and out
Galvanized chain-link fencing
Rock bed (6-8 in. (15-20 cm) rocks)
Exhaust and return ducts to greenhouse
Utility closet
Supply down up ducts
Ceiling supply
Up duct
Supply grills
Drop ceiling
Up duct
Hot air to rock bed
Optional hot air catcher in sunspace

Underfloor plan Reflected ceiling plan

Figure 7. Plans for underfloor and reflected ceiling

Theoretically, the east and west apartments have a larger heating and cooling load and thus require a deeper rock bed than the center apartment with its two common walls. But for convenience in construction, the rock beds for all apartments were constructed the same. The width of the plenum under the kitchen is 5 ft 6 in. (1.65 m), and at the opposite end is 2 ft 0 in. (0.6 m), dimensions established more for ease of access than because of thermal or airflow criteria.

For economic reasons, these rock beds were not placed on top of a concrete floor slab; rather, the earth was leveled, a vapor barrier of 6 mil polyethylene film was laid in a loose sand bed, and the rocks were placed on top. The floors of the plenum areas, however, have concrete slabs.

In this design a concrete slab floor was poured directly on top of the rock bed. Gravel and sand helped level the top surface of the rocks. Then 2 in. (5 cm) of polystyrene foam were laid as insulation and as permanent shuttering for the concrete, which was cast in place with steel mesh for temperature reinforcing. The rigid foam insulation was designed to control but not eliminate heat flows up through the floor.

Instead of a rigid structural support, a soft concept for holding up the faces of the rock bed was devised based on a variation of the "gabion." This technique of a wire basket filled with loose rock is often used in heavy construction for retaining walls and structural rip rap. Gabions were developed in Bologna, Italy, at the end of the last century. Derived from the Italian word "gabbione" (big box), they are not a typical technique in building construction.

In this case loose cylinders of chain-link fencing with a diameter of 4 ft 8 in. to 5 ft 0 in. (1.4-1.5 m) and a height of 4 ft 6 in. (1.35 m) were fabricated by weaving the ends together using a similar piece of wire.

The cylinders were held in place while filled with rocks by a mechanical front loader. When full, the cylinders are not only self supporting, they are also a stable retaining wall for the rock bed behind. The roof of the plenum was spanned by using corrugated metal as a permanent shuttering laid on top of the rock-filled cylinders.

COOLING AND HEATING SYSTEMS

Passive solar gain heats the home in the winter via a sunspace. Patio doors can be opened on either floor for natural air convection to bring heat into the house from the sunspace. Alternatively the fan-forced system can be activated to deliver warm air from the sunspace to the rest of the unit by an overheat thermostat set at 85°F (29°C). The fan-forced system uses the blower from the upper evaporative cooler (with its pads removed) to carry heat from the sunspace and place it in the rock bed for later use. In addition, each house has been wired with four J boxes (1500W, 120V, single phase) for future use of electric resistance baseboard heaters for auxiliary heating. However, these have not been needed or installed in the west unit. In both the center and east units four were installed: a 1200-W heater in a living room space, a 1000-W one in the master bedroom, and two 750-W ones in the smaller bedroom and the upstairs bathroom.

The innovative design of cooling systems for these housing units is based on single-stage evaporative cooling during spring and fall and two-stage evaporative cooling during the monsoon season. A large rock bed is used as a thermal store for coolness collected at night when both ambient and wet-bulb temperatures are significantly lower than during the daytime. This may give a temperature advantage of 30° to 40°F (16°-22°C) temperature difference when compared to daytime operation. Single-stage or direct evaporative coolers are run continuously for 8 to 10 hours through the night and early morning to charge a rock bed with coolness. Since the rocks do not absorb water the result is a bed of cooled, almost-dry rocks.

During the heat of the following day, the system is in a discharge mode: outdoor air is precooled by running it through the cool rock bed as a first stage. Then the cooled air is passed through a single-stage direct evaporative cooler as a second stage before being delivered to the conditioned spaces.

The spent air is exhausted to the outdoors through partially opened windows or preferably through ceiling grills into a vented adjacent space such as an attic. Such an exhaust technique reduces temperatures in thermal transition spaces such as attics, garages, or greenhouses/sunspaces, thus reducing the overall cooling load.

Although numerous experimental, two-stage, evaporative cooling systems have recently been built and operated in the Southwest, this was the first opportunity to build several identical rock beds side by side. Unfortunately, research funds were not available. Thus, although three rock beds were built according to the original plan, one under each housing unit, only one complete system was installed. Even so, the ducts and other mechanical equipment accommodations were all constructed in the other two units to allow future conversion to two-stage evaporative cooling. Only the east housing unit contains an operational two-stage evaporative cooling system as designed.

The middle housing unit currently has only a single one-stage evaporative cooler--the most economical cooling system available for desert locations, except that it is considered ineffective through the monsoon part of the Phoenix summer. In the middle unit the evaporative cooler could in the future be directed to cool the rock bed at night, but there is no two-stage option. Cooling the rock bed under the floor at night would improve the diurnal comfort of the apartment because the rock bed can be a radiant and conductive sink in the daytime. (The system does not have a motorized damper on the outside grille so it needs to be shuttered manually at the end of the cooling season.)

The west unit has a conventional vapor-compression refrigeration heat pump unit--the accepted standard cooling system for total control in this climate. Although calculations indicated that a 1 1/2 ton (5.2 kW) unit was sufficient, a 2-ton (7 kW) unit was installed. This size is still only approximately half the normal size typically installed in comparable housing. The operation of the heat pump is reversed in winter to supplement the passive solar heat contributed by the sunspace.

ELECTRICAL COSTS

The use of operating costs as a comparative measure of cooling effectiveness is crude and inaccurate. It ignores capital investment, maintenance costs, system lifespan, and the cost of money. But from a consumer's perspective, it is the actual out-of-pocket costs that count once the quality of service has been established. For a consumer, the monthly bill is what is truly measurable.

Electrical accounts are rendered monthly to occupants, with meter readings taken generally on the 15th of the month. However, within the 8 months examined, the reading date varied from the 14th to the 18th. In addition, since days per month vary, using average costs per day is more precise than costs per month.

Electrical rate EC-1 consists of three separate charges: a basic service charge, a charge for kilowatt hours used, and a charge for kilowatt demand based on peak use over any 60-minute period, aside from regulatory assessment and sales tax. In the summer of 1983 there was a basic service charge of $10.56/kW of demand. Other charges in the rate changed on 1 July, thus comparisons of costs even within one summer must be relative. After that date a charge was levied of $7.22/kW of demand (but not more than $0.05776/kWh for all kilowatt hours used) plus $0.02446/kWh for all kilowatt hours for bills of 400 kWh or less and $0.03344/kWh for all use for bills of 401 kWh or more, plus assessments and taxes. Before 1 July the additional charges were $6.75/kW capacity but not more than $0.05400/kWh for all kilowatt hours used, plus $0.02446/kWh for all use for bills of 400 kWh or less and $0.03344/kWh for all use for bills of 401 kWh or more. The demand or kilowatt capacity is determined by "The average kw supplied during the 60 minute period of maximum use during the month as determined from readings of the Company's meter." Table 1 compares the three electric bills for September 1983.

Table 1. September 1983 Electric Bills

	Unit and System		
	East Two-Stage Evap.	Center Direct Evap.	West Heat Pump
Basic service	$10.56	$10.56	$10.56
Kilowatt hours	25.38	28.32	53.70
Kilowatt demand	23.83	27.44	39.71
Assessment and tax	2.92	3.24	5.09
Total	$62.69	$69.56	$109.06
Cost/day	$2.02	$2.24	$3.52

Note: Electric bills for three townhouses for the period 15 August to 15 September 1983 (31 days) showing the various charges and the average cost per day.

Typically, houses in Phoenix require cooling over a 6-month period. The intense part of this cooling season runs from mid-May to mid-September, with need for partial cooling for a month on either side of that 4-month period. Electric meter readings made in March and April when mechanical supply of space heating and cooling is not needed were important to establish the base electrical needs for the housing units.

STUDY PARAMETERS

The costs and component contributions of these side-by-side cooling systems cannot be compared exactly using the available information. Yet with only the conventional utility company electric meters standard to a dwelling unit, orders of magnitude can be established and the variables that would affect cooling performance and comparative economics described. The basic discipline of deriving important information from the simplest instrumentation is an important approach.

Various attempts to further isolate the numerous causes of electrical use and especially of demand charges met with confusing results. For instance, readings of the kilowatt-hour meters when each cooling system is turned off compared with those when it is turned on do not account for the randomness of other electrical usage. A full set of event clocks would be necessary to know which appliances and other electrical uses are potentially on over any 60-minute period that establishes the electrical demand charges. Alternatively, the addition of the start-up and running electrical needs of various components of a cooling system requires estimation procedures--a necessary exercise to anticipate electricity service sizing but unnecessary and not very relevant when the actual electricity bills are available.

Climate

The nearest full weather station is at Phoenix Sky Harbor International Airport some 12 miles to the south-southwest. That elevation is 1110 ft (338 m), 155 ft (47 m) lower than the housing site. Spot measurements indicate that the site averages dry-bulb temperatures--4° to 7°F (2°-4°C) lower than Sky Harbor (during the hottest time of a summer day--mid to late afternoon). In design practice, climate information from Sky Harbor is always used in the larger Phoenix metropolitan area although many known microclimatic variations are within the area.

The official records of Monthly Summary of the Local Climatological Data for Phoenix Sky Harbor International Airport show that 1983 was a hotter summer than normal (Table 2). The average temperature was from 2.1°F (1.2°C) higher in June to 6.5°F (3.6°C) higher in September. By the end of October the accumulated cooling degree days (CCD) [based on 65°F (18°C)] were 4344, which was 631 CDD above normal.

Table 2. Monthly Local Climatogical Data - 1983
°F(°C)

	Air Temperatures: DB Max.	Min.	Ave.	Depart from Normal	Dew Point	Heat HDD	Cool CDD	Depart from Normal	%Sun
April	78.3 (25.7)	54.9 (12.7)	66.6 (19.2)	-1.4 (-0.8)	34 (1)	53 (29)	112 (62)	-30 (-17)	89
May	95.0 (35.0)	66.1 (18.9)	80.6 (27.0)	3.6 (2.0)	33 (1)	0	489 (272)	113 (63)	99
June	102.5 (39.2)	74.7 (23.7)	88.6 (31.4)	2.1 (1.2)	36 (2)	0	715 (397)	70 (39)	98
July	107.2 (41.8)	83.8 (28.7)	95.5 (35.3)	3.2 (1.8)	54 (12)	0	951 (528)	105 (58)	86
August	103.8 (39.9)	81.3 (27.9)	92.6 (33.7)	2.7 (1.5)	63 (17)	0	861 (478)	89 (49)	86
September	101.3 (38.5)	80.6 (27.0)	91.0 (32.8)	6.4 (3.5)	63 (17)	0	787 (437)	199 (110)	87
October	87.4 (30.8)	67.0 (19.4)	77.2 (25.1)	3.8 (2.1)	56 (13)	0	388 (216)	115 (64)	85

Note: Monthly averages for the 1983 summer months at Phoenix Sky Harbor show that for the 6-month cooling period the average temperatures were persistently higher than normal, and aside from April the cooling degree days (CDD) [base 65°F (18°C)] ranged from 70 to 199 per month more than normal.

Envelope

Although all three townhouses are identical in layout and construction, the east and west units are exposed to outdoors while the center unit is protected by common walls. This configuration would make the center unit less demanding and could account for savings up to 37% in comparison to the end units. Since the direct evaporative cooler was installed in the middle unit, the costs shown for that system may be unduly low.

Occupancy

The number of occupants and their lifestyles affect the cooling cost of any housing unit. Here all units are occupied by typical middle-income families who were away during the day. Since all three families had lived in Phoenix for some time, they were familiar with local summer cooling needs. The east unit was occupied by an adult and a 12-year old child; the center unit, by two adults and a teenager; and the west unit, by an adult and a 7-year old child. The occupants of the west unit were the least energy conscious, as demonstrated by actions such as leaving windows open for extended periods of time. The occupants of the other two units were moderately energy conscious and preferred an evaporative cooling system because of both costs and comfort.

The occupants of the unit with the heat pump (west) expressed complete satisfaction with their system during the summer. Occupants of the unit with the two-stage evaporative system (east) were also satisfied. They were pleased with the dryness of the conditions and reported that the unit was uncomfortably warm only on a few days. In September occupants of the east unit with its two-stage evaporative system were too cold and needed help in adjusting the automatic controls. Occupants of the center unit with its direct evaporative unit reported that they frequently experienced various degrees of discomfort because of summer heat and humidity.

Comfort

Because home thermostats are notoriously inaccurate, comparing set points is not conclusive. Each cooling system performs according to a range of air change, air velocity, air temperature, and humidity. Thus, the interior conditions of two dwellings cannot be considered identical even though they are both set within a given comfort range. Convenience and response time may also affect the acceptable comfort zone. Furthermore, one or more systems such as the direct evaporative system may not always deliver within the comfort zone. In such cases, the system may have been operating continuously and consuming electrical energy but never quite delivering environmental conditions within the comfort zone.

In this study, which deliberately depends on no instrumentation of interior comfort, interior environmental conditions are assumed comparable between all three units.

Construction Costs and Specifications

Construction materials for the rock beds in all three units cost \$11,000 as built in 1982. This includes excavation, rocks, insulating, stem walls, and power dampers with controls (only in the east unit). Excluded from this cost are footings under the stem walls, slabs and decks above, and all labor.

Duct systems are identical for all three units. Other equipment, costs, and specifications are shown in the equipment schedule in Table 3. Not shown are the timing clocks that switch the two-stage

Table 3. Equipment Schedule

West
"Rudd," two-ton remote heat pump 3TCA024JAS.
  Total 3229 W cooling, SEER 8.0
  Air handler Model UHQA 1000 B.
    Coil RCPBA024S
    Volts 240/208
    Motor HP 1/4, air handler single phase 1/4 HP.
    Motor FLA 2.0
    Ext. static pressure 0.1"
    Cost \$1,500 plus installation

Center
"Dial" - evaporative cooler thermostat control, Model TC-6

Volts	Hz	Amps_{FL}	Amps_{LR}
125	50/60	12	60
277		7	42

cost \$65 each plus installation

Goettle - Model D482 evaporative cooler
  4500 cfm 1/2 HP blower, 9 amps.
  cost \$375 each plus installation

East
"Dial" - same unit
Goettle - same Model D 432 - 482 x 2 units

evaporative system. They begin to evaporatively cool the rock bed at 9:00 p.m. and stop at 7:00 a.m., during which time the motorized damper into the evaporative cooler closet is open to the outdoors. The evaporative cooler that supplies air to the interior space is controlled by a conventional thermostat, which also allows a manual override.

ELECTRICITY USE

Looking at the total electricity used in kilowatt hours (Table 4) confirms that the direct evaporative system used considerably more electricity while delivering less load than the two-stage system. This result is in spite of the fact that the two-stage evaporative system uses two evaporative cooling units while the center unit uses only one. In general, for all three housing units the increase in total electricity used is paralleled by a higher monthly electricity bill in spite of the complex electric rate structure (Table 5).

Table 4. Total Electricity Used in Kilowatt Hours - 1983

	Unit and System		
	East Two-Stage Evap.	Center Direct Evap.	West Heat Pump
March	183	284	418
April	400	77*	356
May	262	36*	373
June	481	383	1036
July	548	851	1429
August	723	943	1924
September	759	847	1606
October	575	874	1366
Totals	3931	4295	8508

*Unoccupied.

Notes: Each monthly reading was taken in the middle of the month, i.e., March = February 15 to March 17.

COST ANALYSES

Because there is only one electric meter on each housing unit, the electrical cost of operating the cooling system cannot be precisely separated from all the other electrical uses in the household. Table 5 shows monthly total cost of the electricity. The wide variation in monthly bills from March or April to August can be attributed primarily to the cost of cooling.

Table 5. Monthly Total Cost of Electricity

	Unit and System		
	East Two-Stage Evap.	Center Direct Evap.	West Heat Pump
March	$23.48	$30.32	$39.40
April	36.83	16.29*	35.18
May	31.83	13.93*	37.91
June	49.84	41.42	81.73
July	45.47	68.33	95.60
August	56.16	69.19	120.30
September	62.69	69.56	109.06
October	50.87	90.82	110.22

*Unoccupied.

Note: See Table 1 for a sample of how the costs are totalled for the month of September.

The best approach in isolating cooling costs would be to look at April as the ideal month when no heating and no cooling are required. Thus the April electric bill could represent the typical base for electrical use for all other purposes (Table 6). Unfortunately, the center unit was not occupied in April. However, the electrical costs in the east and west units in April show that $1.10/day is a reasonable approximation. That figure was also the daily electrical cost for the east unit in May when little if any cooling would have been needed.

By subtracting $1.10/day from the total daily electrical costs during the summer, the cooling costs are approximated (Table 7). There are undoubtedly other methods of extracting the cooling costs from the total electricity used, but this method is the most reasonable for this climate and building type using the available data of a single monthly meter reading.

Table 6. Average Daily Cost of Electricity for All Purposes

	Unit and System		
	East Two-Stage Evap.	Center Direct Evap.	West Heat Pump
March	$0.78	$1.01	$1.31
April	1.15	0.51*	1.09
May	1.10	0.48*	1.31
June	1.72	1.43	2.82
July	1.52	2.28	3.19
August	1.81	2.23	3.88
September	2.02	2.24	3.52
October	1.75	3.13	3.67

*Unoccupied.

Note: Average daily cost of electricity for all purposes including cooling in dollars as averaged from midmonth to midmonth.

Table 7. Average Daily Cost of Electricity for Cooling

	Unit and System		
	East Two-Stage Evap.	Center Direct Evap.	West Heat Pump
May	$0	$ --*	$0.21
June	0.62	0.33	1.72
July	0.42	1.18	2.09
August	0.71	1.13	2.78
September	0.92	1.14	2.42
October	0.65	2.03	2.57

*Unoccupied.

Note: The net balances of cost per day in dollars attributed to cooling costs are derived by subtracting $1.10/day assumed as the average cost of all other electrical uses.

Estimating the cost of water used in the evaporative cooler units is more difficult than isolating cooling costs because there is only one water meter for the entire development. In addition, the use of water by Phoenix families is so variable that average uses for different purposes cannot be easily estimated. Thus, based on other studies (Cook, 1979), the cost of water is assumed to equal approximately 20% of the electrical cost for an evaporative cooler since the cost of water partly reflects the cost of the electricity to pump it through the system (Table 8). However, this particular estimate may be low, especially for the two-stage evaporative cooler system.

Table 8. Estimated Daily Cost of Water for Cooling

	Unit and System		
	East Two-Stage Evap.	Center Direct Evap.	West Heat Pump
May	$0	$ --*	none
June	0.12	0.06	"
July	0.08	0.24	"
August	0.14	0.23	"
September	0.18	0.23	"
October	0.13	0.40	"

*Unoccupied.

Note: Assuming that water costs for evaporative cooling are directly related to electricity needed to run the blower, these daily costs represent 20% of the electricity cost of cooling that must be added.

Another estimate based on a dry-bulb temperature of 100°F (38°C) and a wet-bulb temperature of 80°F (27°C) shows that a standard 5500 nominal cfm cooler will convert 10 gal (38 l) of water per hour into water vapor. With the wet bulb at 60°F (16°C), the amount of water vaporized would double. Assuming an average use of 100 gal/day (38 l/day) and a water cost of $0.02 for 10 gal (38 l), the daily water cost would be $0.20 or approximately $6/month. Such a cost represents a median of the estimates proposed in Table 8 and thus confirms its order of magnitude.

SAMPLE DAY

A sample set of temperatures was taken on 28 August 1984, a typical summer monsoon day. The official maximum readings at Sky Harbor Airport between 3:00 and 5:00 p.m. were 102°F (39°C) dry bulb, 65°F (18°C) dew point, and 30% relative humidity. The previous night's low was 82°F (28°C) so the average temperature was 92°F (33°C) compared with 88°F (31°C), which is the normal official average for that date. On that day the east apartment was unoccupied. Windows were left partially open and the cooling system was run by pulling outside air into the sunspace, through the cooled rock bed and then, without any further cooling, into the house itself. The air temperature from the rock bed into the house was a steady 84°F (29°C) at the end of the day, presumably at the end of the diurnal cooling pulse in the rock bed. At the same time, between 5:00 and 5:30 p.m. the dry-bulb air temperature on site dropped from 98° to 94°F (36° to 34°C). Presumably the occupants of the east unit on returning home would change the cooling mode, to initiate the night evaporative cooling of the rock bed, and simultaneously turn on the direct evaporative cooling.

CONCLUSIONS

In this study the two-stage evaporative system has clearly provided more comfortable summer cooling and a significantly lower cost than direct evaporative cooling. In general, the pattern of operational cooling costs as experienced in summer 1983 confirms calculated predictions. The operating costs of evaporative cooling, whether as a direct or a two-stage system, are substantially lower than those of a vapor compression heat pump system (Table 9). Where direct evaporative systems are equally effective such as Tucson, Arizona, typical commercial advertising states that evaporative coolers will "save 3 out of 4 dollars" over refrigerated air conditioning (Cook, 1979). Practical experience in Tucson confirms those claims.

Table 9. Estimated Daily Total Cost for Cooling

	Unit and System		
	East Two-Stage Evap.	Center Direct Evap.	West Heat Pump
May	$0	$ --*	$0.21
June	0.74	0.39	1.72
July	0.50	1.42	2.09
August	0.85	1.36	2.78
September	1.10	1.37	2.42
October	0.78	2.43	2.57

*Unoccupied.

Note: Each total includes the approximate cost of electricity plus a 20% allowance for the cost of water used in both direct evaporative coolers and two-stage evaporative coolers.

In Phoenix, with a more demanding summer climate, such claims cannot be made so conclusively because complete comfort cannot be delivered by direct evaporative coolers. The intensity of the summer heat in 1983 resulted in even less satisfactory performance from direct evaporative systems. Thus, two-stage evaporative coolers provide the only reasonable comfort alternative to heat pumps for cooling in a Phoenix climate that is currently available.

Table 10 shows that the daily total cost for cooling by the two-stage evaporative system ranges from 24% to 45% the cost of cooling by a heat pump. Over the 5-month period of the summer of 1983 the average cost was approximately 35% or one third. Therefore, it has been demonstrated that in the Phoenix climate a two-stage evaporative system can deliver summer cooling comfort at one-third the operating cost of a conventional vapor compression refrigeration system.

Table 10. Estimated Daily Percentage Cost for Two-Stage Evaporative Cooling

	Two-Stage Evap.
June	0.43
July	0.24
August	0.31
September	0.45
October	0.32
Season Average	0.35

Note: Assuming heat pump cooling as the standard 100% cost, these are the monthly percentage cooling costs for two-stage evaporative cooling. Note the lowest cost is in the hot, dry, early part of summer and the higher costs are during the late summer monsoon when evaporative techniques are less effective.

Further study is desirable to confirm and optimize design procedures, reduce construction costs, compare comfort levels and convenience, and match equipment components against electrical demand-rate structures. In addition the parameters of interior comfort should be monitored: dry bulb, wet bulb, and air motion. However, this comparative study of side-by-side operating systems clearly demonstrates the economies of two-stage evaporative cooling systems in the most demanding U.S. hot desert climate as represented by Phoenix, Arizona.

REFERENCES

Arizona Solar Energy Commission, 1981. Solar Designs for Arizona Homes. WSUN/149, Phoenix, AZ, pp. 36-39.

Cook, Jeffrey, 1979. Cool Houses for Desert Suburbs. Phoenix, AZ: Arizona Solar Energy Commission, p. 126.

Cook, Jeffrey, 1983a. Innovative rock bed construction. Progress in Solar Energy. Boulder, CO: ASES, Vol 6, pp. 59-61.

Cook, Jeffrey, 1983b. Rock bed design and construction for heating and cooling. Passive and Low Energy Architecture - The Second International PLEA Conference. Oxford, England: Pergamon Press, pp. 361-370.

APPENDIX: MONITORING AND SIMULATION OF SUNSPACE EAST UNIT

The Arizona Solar Energy Commission (ASEC) installed thermal sensors during construction and collected both weather information and thermal data throughout the summer of 1983. Its report of monitored information is not yet available. However its investigation of infiltration revealed that, at less than 1/2 air change per hour (ach), the east unit was the tightest construction the ASEC team had measured throughout the state. Since the ASEC had completely instrumented this unit no attempt was made to duplicate its work in this study.

The contractors for that study (ASEC #401), the Solar Energy Research Facility, University of Arizona at Tucson, did, however, compute energy analyses and annual simulated heating and cooling loads using an ENTRAK model. The following (including Table A-1) is quoted from the draft report, an analysis that emphasizes the conservation aspects of the design.

> The cooling season begins around the first half of March and extends into late November, as is expected of the

Phoenix climate. The heating season is short and the space heating requirement is very small. The Sunspace Apartments have a noticeably low cooling load for the Phoenix climate. For comparison the Payson House cooling load in August is approximately 1.3 times that of the Sunspace Apartments, even though Payson experiences much cooler summers. The low cooling load may be due to the fact that the roof area is only 540 square feet. Furthermore, a maximum of three walls are exposed to the exterior environment as each unit is adjacent to another unit. The unit in the center only has two exposed walls. Since a majority of the residential space heating and cooling loads are due to the roof and wall exposures, reducing these areas would result in tremendous energy savings in conditioning the building.

The Sunspace Apartments require approximately three (3) months of space heating and nine (9) months of space cooling. Maximum heating load occurs in January while maximum cooling load occurs in August. The January heating load is 2.5 GJ (2.4 MBtu). The August cooling load is 10.3 GJ (9.8 MBtu). Annual heating load is 8.0 GJ (7.6 MBtu); annual cooling load is 73.3 GJ (69.0 MBtu).

It can be concluded that the Sunspace Apartments are energy efficient since the space heating and cooling requirements are so small. The main reason for the low space conditioning load is the building's modest amount of exposed area. The total floor area of each unit is about 1,100 square feet, yet the roof area is only 540 square feet because of the two-story construction. Since each unit is adjacent to at least one other unit, the exterior walls' exposure is reduced. Furthermore, the length of the east and west walls is much longer than that of the north and south walls; and there is no glass exposure on the east or west wall. These factors plus the SE-orientation of the building all contribute to a substantial reduction in radiation gain in summer.

The Sunspace Apartments are very well-constructed and well-designed. Even without the inclusion of the two-stage evaporative cooling system, the water tubes, and the rockbed in the simulation, the results show that these apartments have negligible heating requirement and very modest cooling requirement.

Table A-1. ENTRAK Load Simulation Results for East Unit

	Monthly Load Per Apartment Unit	
	GJ/mo	MBtu/mo
January	- 2.5	- 2.4
February	- 1.8	- 1.7
March	- 1.9	- 1.8
April	7.3	6.9
May	8.4	8.0
June	9.7	9.2
July	10.1	9.6
August	10.3	9.8
September	8.7	8.3
October	9.6	9.1
November	8.5	8.1
December	- 1.8	- 1.7
Annual Heating	- 8.0 GJ	- 7.6 MBtu
Annual Cooling	72.6 GJ	69.0 MBtu

Passive Solar Journal, 3(1), 33-76 (1986)

Natural Convection Research and Solar Building Applications

Ren Anderson
Solar Energy Research Institute
1617 Cole Boulevard
Golden, CO 80401

Abstract

The study of natural convection flows in enclosed spaces is one of the most active areas of heat transfer research today. Solar energy applications have provided a major stimulus for this research because of the importance of natural convection as a heat transfer mechanism in passive solar buildings and solar collectors. The results of this research are summarized and recommendations are made for future research areas that will result in further improvements in the performance of solar buildings.

Copyright © 1986 by Marcel Dekker, Inc.

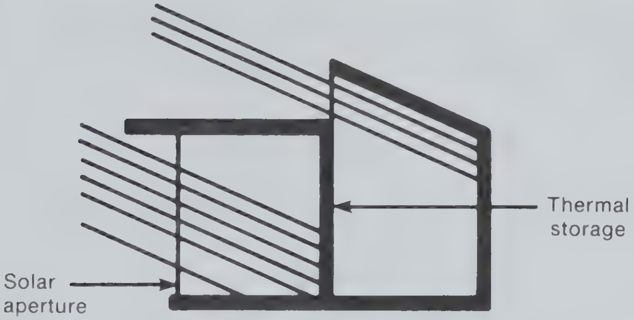
INTRODUCTION

A passive solar system has been defined by Balcomb (1981) as "one in which the thermal energy flow is by natural means." Most passive designs use south-facing glass as the solar collection element and the building's structural mass as the thermal storage element. A successful passive design requires integration of the solar collection, thermal storage, and heat distribution functions into the architecture of the building. A thorough understanding of natural convection in enclosed spaces is absolutely necessary to successfully achieve this integration without sacrificing the comfort standard of conventional heat systems.

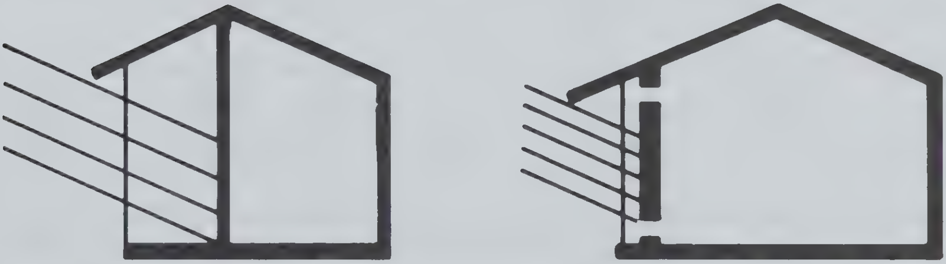
Passive applications range from small flat-plate thermosiphon collectors to various types of solar buildings components including Trombe walls, atria or sunspaces, and direct gain windows. Solar buildings can also incorporate vents or windows for ventilation cooling. As shown in the schematic diagrams of the main types of solar buildings in Figure 1, their geometries and thermal boundary conditions vary widely. In real applications, buildings are complicated further by the addition of furniture, draperies, and wall coverings.

This paper summarizes recent research findings on natural convection flows in enclosures from the viewpoint of solar building applications. This review focuses on the basic physical mechanisms that drive natural convection heat transfer in enclosures. Forced convection effects caused by air infiltration and natural ventilation through open doors and windows are not considered. Previous reviews of natural convection either have been general (Catton, 1978; Ostrach, 1982) or have been limited specifically to flat-plate solar collector applications (Buchberg, Catton, and Edwards, 1976). A recent review by Barakat (1985) summarizes research on natural convection between building zones, but does not examine the impact of natural convection on heat transfer through the building envelope or the effects of complicated building configurations.

In the following section, we describe some of the basic parameters that determine the characteristics of natural convection in solar buildings. We then review current research results relevant to natural convection effects on energy use at the building envelope,



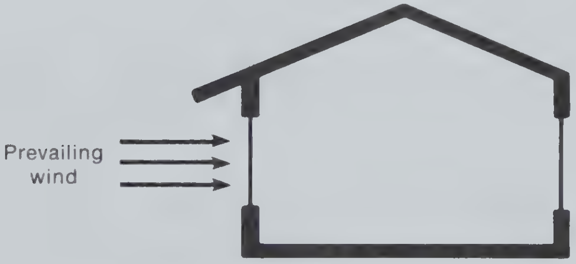
(a)Direct gain



Sunspace

(b) Indirect gain

Trombe wall/Thermosiphon air panel



(c) Ventilation cooling

Figure 1. Schematic diagrams showing several types of solar buildings

natural convection within a single building zone, and convection between building zones.

We conclude the review by outlining important research areas in which our present understanding is incomplete.

CHARACTERISTICS OF NATURAL CONVECTION FLOW IN BUILDING GEOMETRIES

Window location and orientation are features of a passive solar home that distinguish it from a conventional home. A typical passive solar home has most of its windows on the south side. The thermal forcing produced by the absorption of solar energy and the presence of cold sinks, such as windows and thermal storage, produce strong free convection flows. These flows are the primary heat transfer mechanism between different building zones. Natural convection is also significant in determining the heat losses through external building surfaces and the heat transfer within single building zones.

Natural convection flows are created by density differences between the air at different locations inside a building. These differences are produced by differences between the temperatures of various building surfaces. Hot building surfaces result from solar illumination, auxiliary space heating systems, or thermal storage material that has been previously charged with heat. Cold surfaces result from windows, or thermal storage materials that have been discharged. South-facing windows and thermal storage materials can act as either cold sinks or hot sources, depending on the time. During the day, thermal storage materials act as cold sinks and south-facing windows act as hot sources. During the night, south-facing windows act as cold sinks and thermal storage materials act as hot sources. Natural convection flows are strongly influenced by building geometry and thermal boundary conditions. The overall objective of natural convection research has been to quantify the effects of surface temperature distributions and geometry on energy transport in natural convection applications.

To simplify the reporting of natural convection heat transfer results, they are commonly expressed in terms of nondimensional parameters. Nondimensional parameters provide a concise method of describing the geometry and surface temperature boundary conditions that influence the natural convection flow. The nondimensional parameters used in this review include:

the Rayleigh number

$$Ra = \frac{g\beta H^3 \Delta T}{\nu\alpha} , \qquad (1)$$

the flux modified Rayleigh number

$$Ra^* = \frac{g\beta H^4 q}{\nu\alpha k} , \qquad (2)$$

the Prandtl number

$$Pr = \frac{\nu}{\alpha} , \qquad (3)$$

the room aspect ratio

$$A = H/L , \qquad (4)$$

and the Nusselt number

$$Nu = \frac{\bar{h}H}{k} . \qquad (5)$$

In Equations 1 through 5, g is the gravitational acceleration, β is the coefficient of thermal expansion, ΔT is the characteristic temperature difference, ν is the kinematic viscosity, α is the thermal diffusivity, k is the thermal conductivity, q is the surface heat flux, H is the height of the room, L is the length of the room, and $\bar{h}$ is the average natural convection heat transfer coefficient. The Nusselt number is a nondimensional heat transfer coefficient, the Rayleigh numbers define the temperature or heat flux boundary condition on a particular surface, the aspect ratio defines room geometry, and the Prandtl number defines the impact of fluid properties. Air has a Prandtl number of 0.7 and water has a Prandtl number of about 7. Prandtl number changes over the range $0.7 \le Pr \le 7$ affect average heat transfer results by only 10% to 15% when the flow is laminar (Bohn and Anderson, 1984).

The aspect ratio in building applications can be large or small. The Trombe wall is a large aspect ratio configuration with vertical parallel surfaces formed by the window and storage wall. Other types of solar buildings (sunspace, direct gain) have aspect ratios close to one. A number of thermal boundary conditions are possible, and many of them are quite complex. The Rayleigh numbers in building applications are on the order of 1×10^{10}. Depending on the specific application, the natural convection flow may be laminar, partially turbulent, or fully turbulent. For natural convection flows next to a vertical heated or cooled surface at large Rayleigh numbers, velocity changes and air temperature changes are limited to a thin region directly adjacent to the surface (Figure 2). This near-wall region is known as a boundary layer. The air flows produced by all of the thermally active surfaces in a building combine to determine the overall natural convection circulation pattern in the building. Figure 3 shows schematic circulation patterns for two simple configurations. The boundary layers on heated and cooled surfaces combine to form a closed circulation loop that transports energy throughout the building.

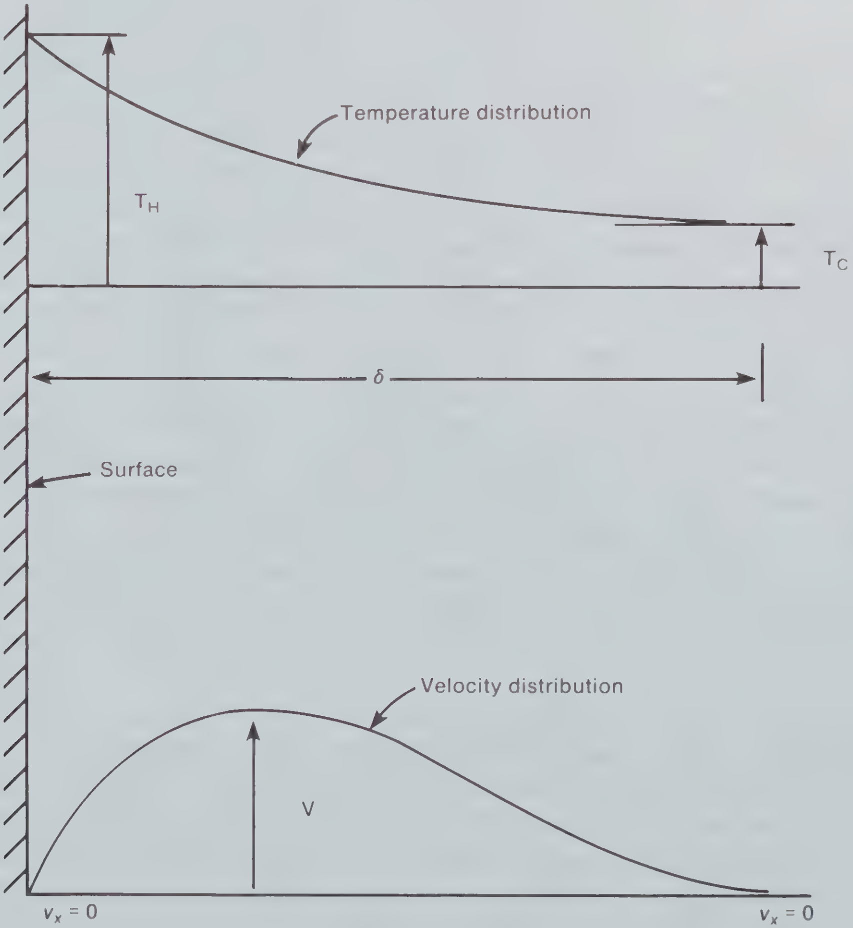
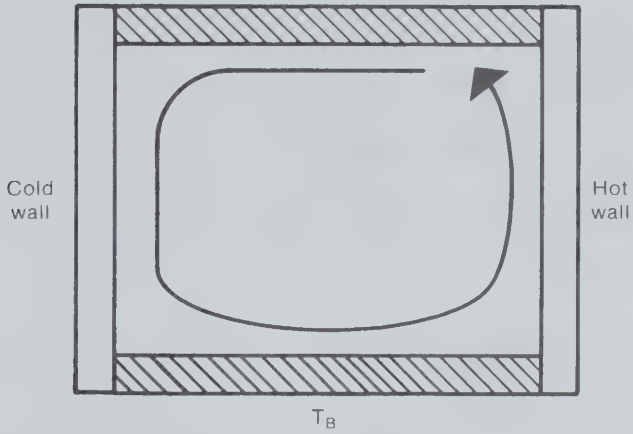
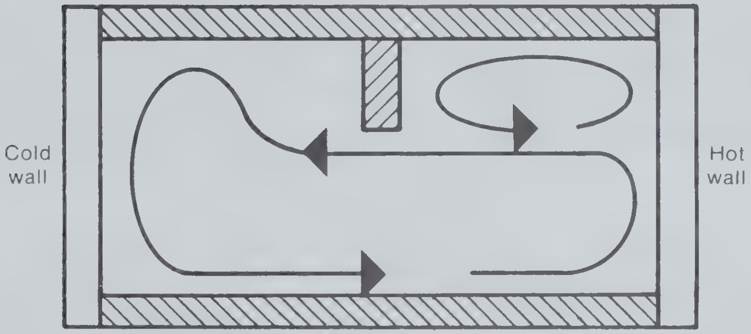


Figure 2. **Schematic diagrams showing temperature and velocity distributions in the natural convection boundary layer next to a heated vertical wall** Source: Chapman, 1974



(a) Direct gain



(b) Indirect gain

Figure 3. Simple thermal models for solar building applications showing example circulation patterns (see also Figure 1)

The air velocity, boundary layer thickness, and average heat transfer coefficient for laminar boundary layers can be estimated from the relations:

$$V \sim \frac{\alpha}{H} Ra^{\frac{1}{2}} , \tag{6}$$

$$\delta \sim \frac{H}{Ra^{\frac{1}{4}}} , \text{ and} \tag{7}$$

$$\bar{h} \sim \frac{k}{H} Ra^{1/4} \tag{8}$$

where V and δ are the average air velocity and boundary layer thickness, respectively. In Equations 6 through 8, the temperature difference between the wall and room air is constant, and the room air is unstratified.

These simple relationships do not explicitly include the effect of room aspect ratio. Bejan (1980) has provided a synthesis of analytical results demonstrating the dependence of the Nusselt number on aspect ratio for laminar flow in two-dimensional enclosures with adiabatic horizontal walls. Figure 4 shows this dependence. The heat transfer is reduced in large aspect ratio enclosures because direct contact between the hot and cold surfaces is reduced as the aspect ratio increases. The heat transfer is also reduced in low aspect ratio enclosures but by a different physical mechanism. In low aspect ratio enclosures, the heat transfer is reduced as a result

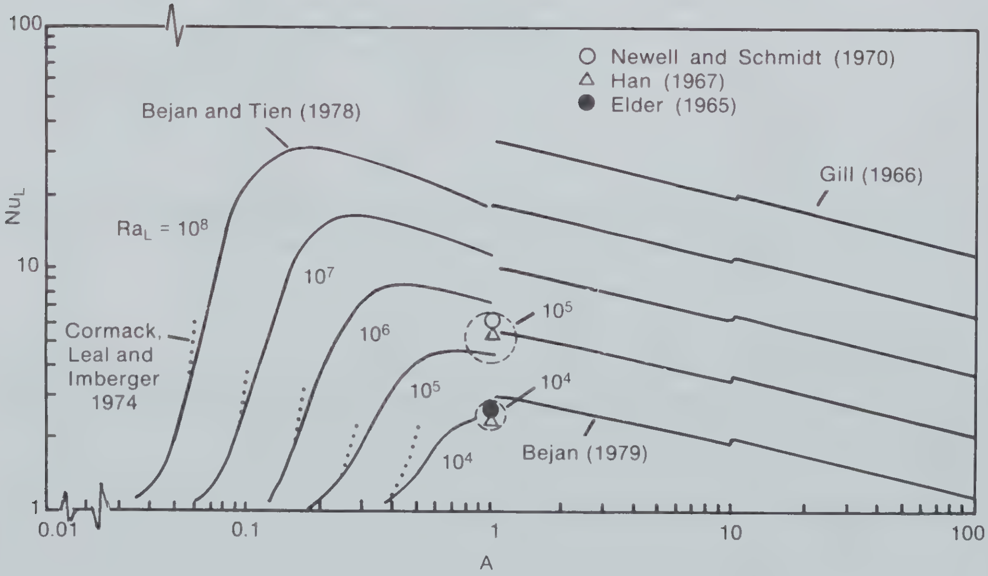


Figure 4. Effect of room aspect ratio A upon Nusselt number Nu in enclosures with heated and cooled end walls

of the increased drag produced by the presence of the horizontal boundaries. In enclosures with aspect ratios of one at high Rayleigh numbers, the primary effect of adiabatic horizontal boundaries is to turn the boundary layer flow created by the vertical walls. These turned boundary layers thicken and traverse the top and bottom of the enclosure.

NATURAL CONVECTION HEAT TRANSFER THROUGH THE BUILDING ENVELOPE

Single-Pane Windows

Numerous investigators have examined the combined natural convection/conduction heat transfer through a vertical surface that separates reservoirs at different temperatures. Studies by Lock and Ko (1973), Anderson and Bejan (1980), and Viskanta and Lankford (1981) examined heat transfer through a vertical plate separating semi-infinite fluid reservoirs. Sparrow and Prakash (1981) conducted a numerical investigation of an enclosure that was coupled via a conductive wall to an external natural convection flow.

Figure 5 compares the relative importance of indoor radiation and convection heat losses through a single-pane window as a function of indoor-outdoor temperature difference and external wind velocity. Figure 6 shows schematic flow patterns for each case. In each case the radiation component is roughly the same size as the natural convection component.[1]

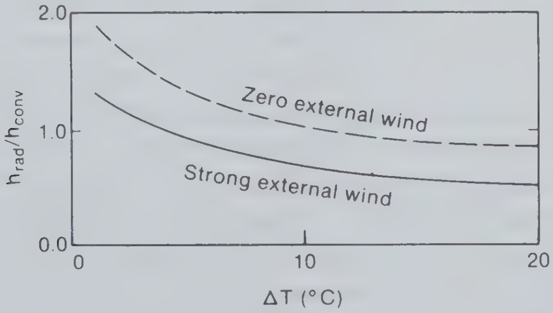


Figure 5. Relative importance of radiation and convection losses through a single-pane window as a function of indoor-outdoor temperature difference and wind velocity

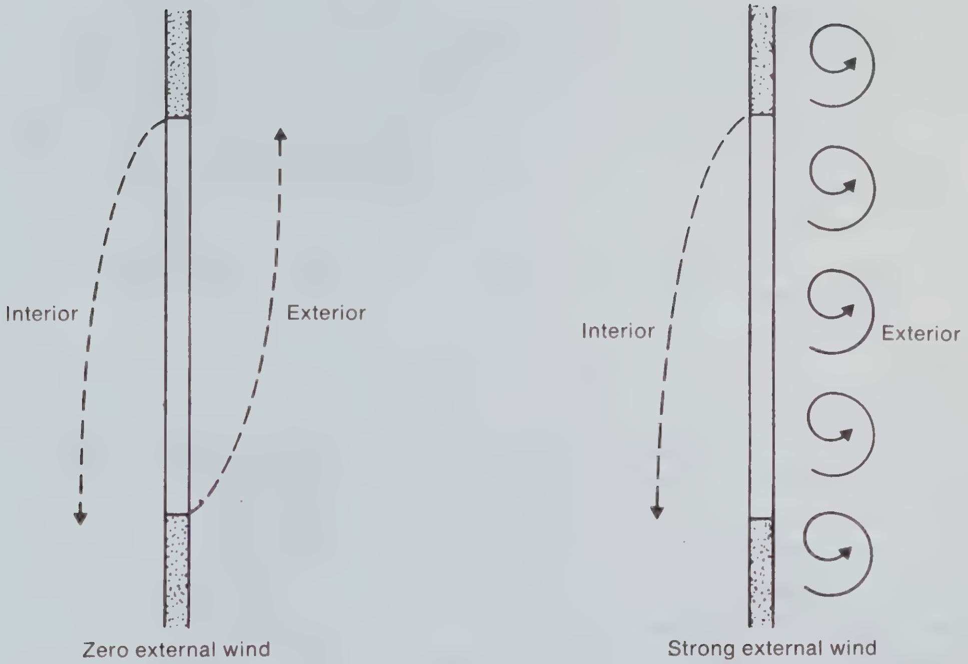


Figure 6. Air flow patterns for convection heat transfer through a single-pane window (arrows indicate direction of flow)

Double-Pane Windows

Almost all new construction in the United States uses double-pane windows because of their superior insulating qualities. Korpela, Lee, and Drummond (1982) have carried out a series of numerical experiments on large aspect ratio enclosures for the specific application of double-pane windows. They were primarily interested in determining the optimum spacing between the panes for minimum heat loss. As the spacing between the windows was reduced at constant window height, the flow in the cavity exhibited in succession a conduction-dominated unicellular flow, a multicellular flow, and finally reverted to a unicellular flow. The final unicellular flow was not a boundary layer flow but was in the transitional regime between conduction- and convection-dominated heat transfer. The minimum heat transfer was found to occur at the onset of the final multicellular flow. Korpela, Lee, and Drummond suggest the following formula for calculating the optimum aspect ratio for minimum natural convection and conduction heat transfer as a function of the Rayleigh number:

$$A^3 + 5A^2 = 1.25 \times 10^{-4} \text{ Ra/Pr} . \tag{9}$$

For the high-aspect ratios typical of window applications, Equation 9 can be simplified to the form

$$L_{opt} = 20 \left(\frac{\nu\alpha}{g\beta\Delta T}\right)^{1/3} . \tag{10}$$

Equation 10 indicates that the optimum window spacing for minimum convective and conductive heat transfer is independent of the window height and inversely proportional to the temperature difference raised to the one-third power. For an air temperature difference of 10°C (18°F) this optimum spacing can be calculated to be ≈2 cm (0.8 in.). ElSherbiny, Raithby, and Hollands (1982) have conducted an extensive series of experiments in large aspect ratio enclosures that are consistent with the height independence predicted by Equation 10. They found that for A > 40 the transition between conduction- and convection-dominated heat transfer was independent of the aspect ratio, when the enclosure spacing was held constant.[2]

NATURAL CONVECTION WITHIN A SINGLE BUILDING ZONE

Heating and Cooling of Vertical Surfaces

The thermal boundary conditions in passive solar applications are generally three-dimensional, include heating and cooling of several walls at one time, and involve heating conditions that span the range from constant temperature surfaces to constant heat flux surfaces.

Balvanz and Kuehn (1980) have shown that the effect of finite wall conductivity can be significant, particularly for the case of a constant flux boundary condition. On a heated vertical wall subjected to a constant flux boundary condition, the temperature of the wall must increase with vertical location to maintain a constant driving temperature difference between the wall and the fluid in the boundary layer next to the wall. Conduction in the wall reduces the wall temperature gradient and produces a corresponding decrease in heat transfer from the wall. Figure 7 shows the wall temperature profile

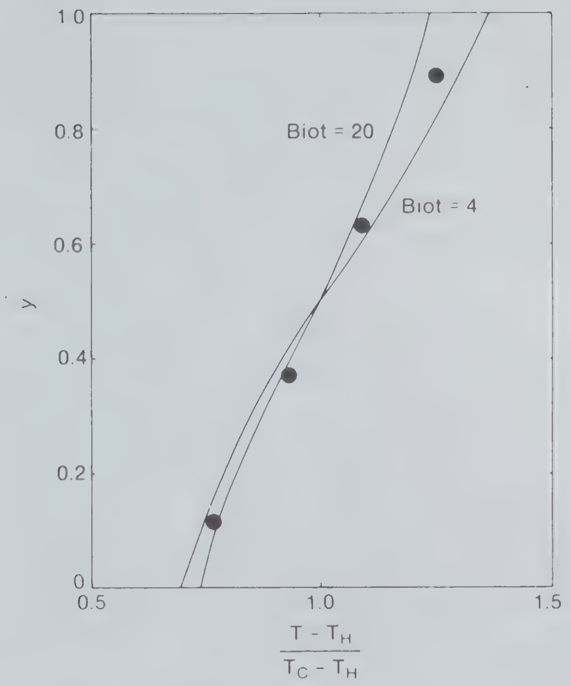


Figure 7. Effect of wall Biot number upon wall temperature distribution for a constant flux boundary condition

in a wall with Bi = 10 as measured by Anderson and Bohn (1984). Figure 8 shows the corresponding decrease in heat transfer predicted by Balvanz and Kuehn. The quantity Bi is the Biot number, a non-dimensional expression for the thermal conductivity of the wall. Large Biot numbers imply large wall thermal conductivity.

MacGregor and Emery (1969) conducted numerical calculations of natural convection flow in an enclosure and varied the thermal boundary condition on the heated wall. They found that convective heat transfer for a constant flux condition was 30% higher than when the heated wall was isothermal. The average temperature difference between the hot and cold wall was used in the definition of the Nusselt number for the constant flux surface. Schinkel and Hoogendoorn (1983) repeated the calculations of MacGregor and Emery for $Ra_L = 5.8 \times 10^4$ and found an increase of 20%. This prediction was found to agree with experiments done in air. Schinkel and Hoogendoorn have also done experimental comparisons

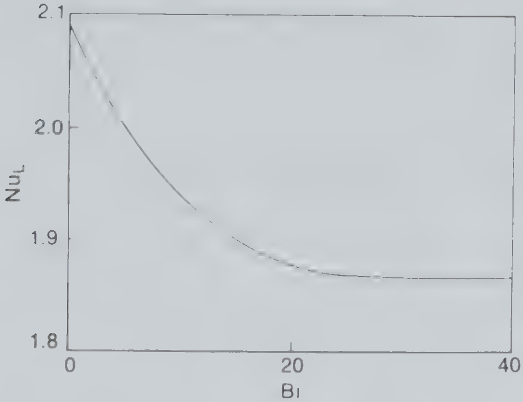


Figure 8. Effect of wall Biot number upon wall heat transfer for a constant flux boundary condition

at θ = 60°, 40°, and 20° and found increases of 15%, 11%, and 9%, respectively, where θ is tilt angle of the enclosure with respect to the horizontal.

Depending on window spacing, direct solar gain may result in a series of localized heated areas rather than uniform heating of an entire wall. Jaluria (1982) conducted a numerical study of the interaction of multiple horizontal heated strips on a vertical surface in the boundary layer regime. He found that the velocity increased and the temperature decreased as one moved downstream from the region of heating. Heat transfer from upstream heaters was enhanced if they were far enough upstream to benefit from the velocity produced by downstream heaters without being exposed to hot fluid. Kubleck, Marker, and Straub (1980) examined convection in enclosures with nonuniformly heated walls. They conducted a two-dimensional transient numerical analysis of a square box with one vertical wall heated on its lower half and cooled on its upper half. All other walls were insulated. The unstable stratification produced by this heating and cooling arrangement resulted in two vertically displaced convection cells that grew and decayed with time. Chao, Ozoe, and Churchill (1981) investigated theoretically the effect of sawtooth variations in the temperature of an inclined enclosure with an aspect ratio (H/L) of two. They found that the surface temperature variations produced a stronger circulation and a higher overall Nusselt number than did a uniform temperature.

Natural convection flows in enclosures differ from external natural convection flows because the flow recirculates and thus interacts with itself. It is difficult to model this interaction accurately through the use of external flow results applied to internal flows with the same surface temperature. However, it has been common practice to calculate building heat loads based on external flow results because detailed enclosure flow results did not exist until recently. Bauman, Gadgil, Kammerud, Altmayer, and Nansteel (1983) compared the correlations resulting from these two approaches and found the loads calculated from enclosure results to be 30% to 50% lower than results based upon correlations for isolated surfaces. Altmayer, Gadgil, Bauman, and Kammerud (1983) conducted a series of numerical experiments aimed at developing an improved set of correlations. They succeeded in providing a series of correlations that improved the other existing methods; however, the correlations are also substantially more complicated than existing methods.

Bohn, Kirkpatrick, and Olsen (1984) examined heat transfer in a cubical enclosure with heating and cooling of multiple vertical walls. They found that the heat transfer within the enclosure for any combination of hot and cold walls could be based on the area-weighted bulk temperature difference,

$$\Delta T_b = |T_i - T_b| \tag{11}$$

where

$$T_b = \frac{\Sigma_i\ T_i A_i}{\Sigma_i A_i} \tag{12}$$

and T_i and A_i are the temperature and the area, respectively, of surface i.

By using ΔT_b to define the heat transfer coefficient, Bohn, Kirkpatrick, and Olsen could express the heat transfer results for all of their experiments by one correlation. Bohn and Anderson (1986) subsequently found that the bulk temperature defined by Equation 12 closely predicted the measured average core temperature in a cubical enclosure with three-dimensional thermal boundary conditions on its vertical walls. This result is important because it demonstrates that the heat transfer in the boundary layer regime in an enclosure with complicated thermal boundary conditions on the vertical walls is driven by the temperature difference between a given surface and the bulk fluid temperature in the core of the enclosure.[3]

Heating and Cooling of Horizontal and Vertical Surfaces

In building applications the floor and ceiling, like the walls, can be active heat transfer surfaces. The temperature distributions on the floor and ceiling can profoundly affect the flow patterns, thermal stratification, and heat transfer.

Ostrach and Raghavan (1979), Fu and Ostrach (1981), Shiralkar and Tien (1982), and Kirkpatrick and Bohn (1983 and 1986) have examined the effect of vertical- as well as horizontal-wall-temperature differences on natural convection in enclosures with four active heat transfer surfaces. Figure 9 shows cross-sections of the thermal boundary conditions that were used in these studies.[4]

Ozoe, Mouri, Hiramitsu, Churchill, and Lior (1984); Anderson, Fisher, and Bohn (1985a); and Anderson and Lauriat (1986) have examined the effects of heating and cooling of horizontal and vertical surfaces in enclosures for the case when less than four surfaces are thermally active. Ozoe et al. studied natural convection in a single building zone with a heated floor and a vertical wall that was cooled over 57% of its length. They conducted numerical calculations using a two-equation model of turbulence for $Ra = 10^6$ and found the flow to be weakly three dimensional with a horizontal boundary layer next to the heated floor. Ozoe et al. did not consider the heat transfer aspects of the problem.

Anderson and Lauriat conducted a numerical study of natural convection in a closed cavity with an isothermal vertical wall that was cooled over its entire length, and a heated floor. The heat transfer and flow patterns were calculated for cases when the floor was isothermal as well as for cases when the floor was a constant heat flux surface. A horizontal boundary layer was found to form next to the heated floor, in agreement with numerical calculations by Ozoe et al. and experimental observations by Anderson, Fisher, and Bohn (1985a). The structure of the horizontal boundary layer calculated

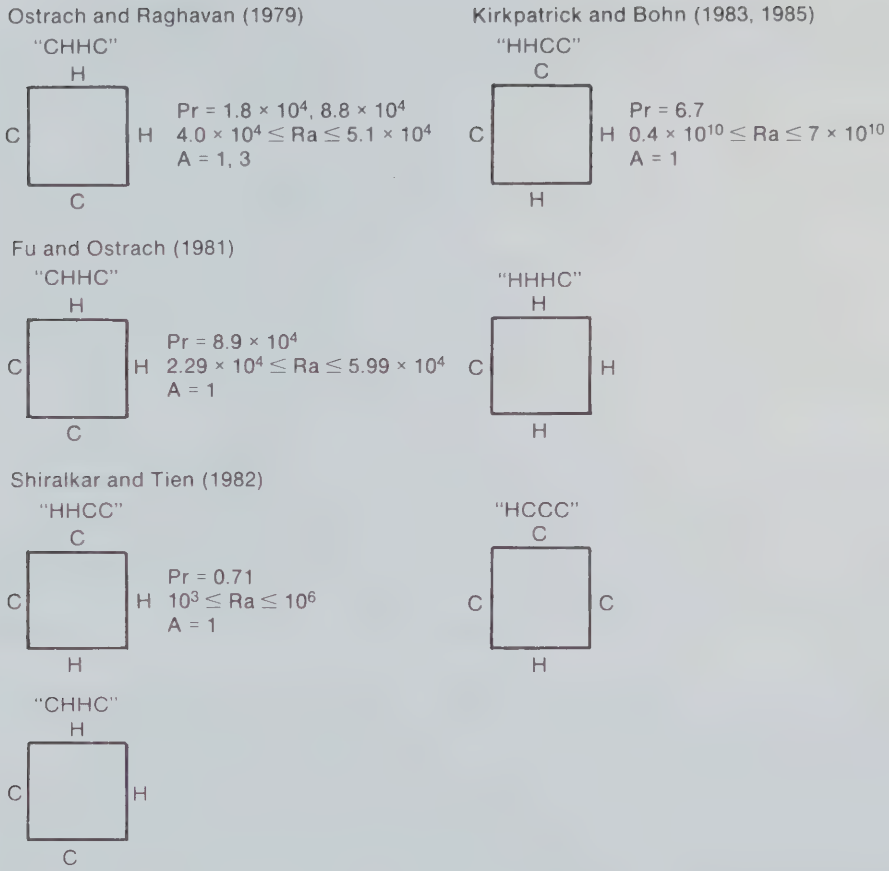

Ostrach and Raghavan (1979)
"CHHC"
H
C
H
C
Pr = 1.8 × 10^4, 8.8 × 10^4
4.0 × 10^4 ≤ Ra ≤ 5.1 × 10^4
A = 1, 3
Kirkpatrick and Bohn (1983, 1985)
"HHCC"
C
C
H
H
Pr = 6.7
0.4 × 10^10 ≤ Ra ≤ 7 × 10^10
A = 1
Fu and Ostrach (1981)
"CHHC"
H
C
H
C
Pr = 8.9 × 10^4
2.29 × 10^4 ≤ Ra ≤ 5.99 × 10^4
A = 1
"HHHC"
H
C
H
H
Shiralkar and Tien (1982)
"HHCC"
C
C
H
H
Pr = 0.71
10^3 ≤ Ra ≤ 10^6
A = 1
"HCCC"
C
C
C
H
"CHHC"
H
C
H
C

Figure 9. Summary of enclosure correction studies with vertical and horizontal heat fluxes

by Anderson and Lauriat is shown in Figure 10. They compared their heat transfer results to correlations for horizontal and vertical surfaces in unconfined flows. The unconfined flow correlations overpredicted heat transfer from the vertical wall by 13% and underpredicted heat transfer from the floor by 40%.

Anderson, Fisher, and Bohn experimentally examined the flow structure, heat transfer, thermal stratification, and temperature distributions in an enclosure with a heated floor and heated and cooled side walls. During their experiments they varied the relative level of heating to the floor and one vertical wall between the range 0 ≤

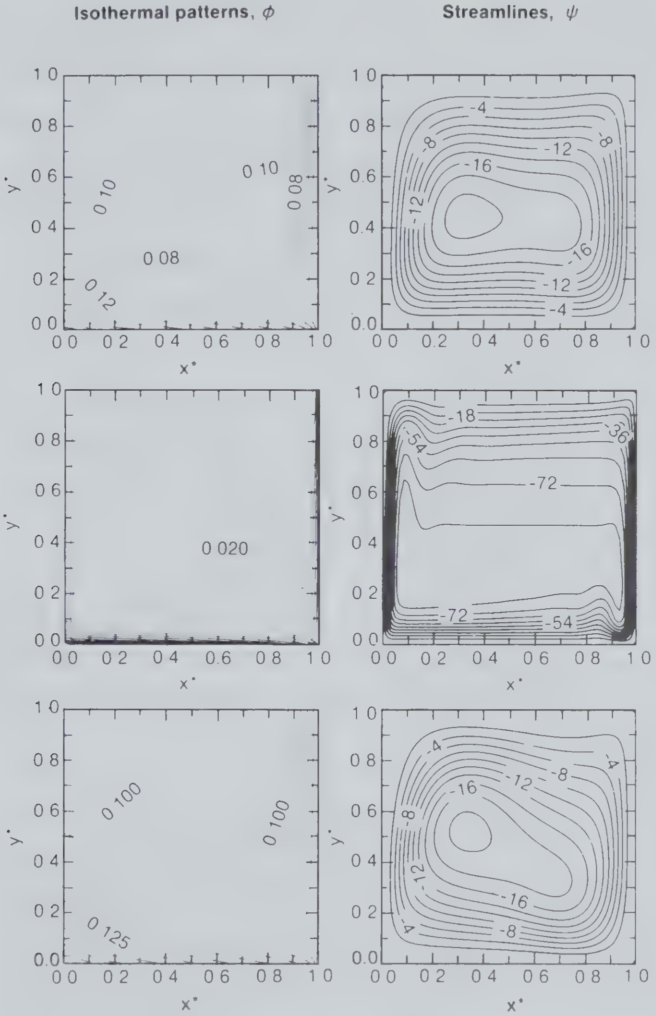


Figure 10. Streamlines and isotherms showing the structure of the horizontal boundary layer flow next to the heated floor of an enclosure with an insulated ceiling

PWR ≤ ∞. The parameter PWR is the ratio of the energy per unit area convected from the floor divided by the energy per unit area convected from the vertical wall. When PWR = 0, the problem becomes that of a closed cavity with differentially heated end walls. When PWR = ∞, the problem reduces to that of a cavity with a heated floor and a cooled vertical wall studied by Anderson and

Lauriat. Anderson, Fisher, and Bohn (1985b) found the level of the thermal stratification in the cavity to be a strong function of the level of heating provided to the floor (Figure 11). The minimum level of thermal stratification occurred for floor heating only (PWR = ∞). Anderson, Fisher, and Bohn (1985b) used these results to calculate the total convection energy transport from the hot walls to the cold wall over the range $0 \leq \text{PWR} \leq 4$. Their results are plotted in Figure 12. The convective transport for PWR = 4 was found to be a factor of two smaller than the convective transport for PWR = 0.

Anderson, Fisher, and Bohn concluded that floor heating decreases thermal stratification and decreases convective energy transport to the cold wall while side wall heating increases thermal stratification and increases convective energy transport to the cold wall. For applications where the cold wall represents a heat loss, floor heating is more effective than side wall heating because it minimizes energy losses. However, if the cold wall represents a convectively coupled thermal storage wall, then convective transport to the storage wall is maximized by absorbing incoming solar energy on a vertical surface rather than on the floor.

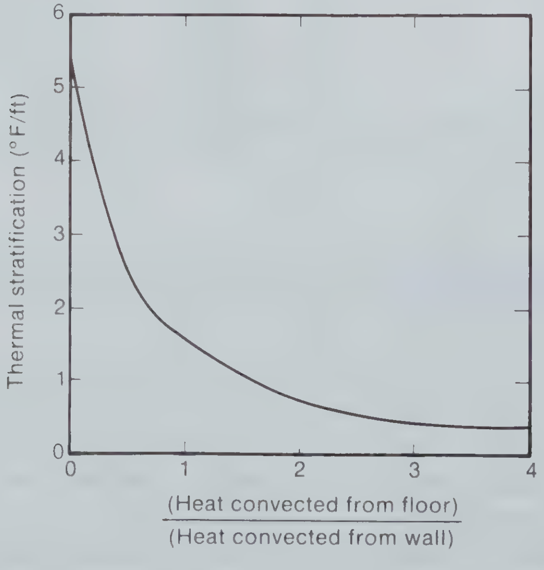


Figure 11. **Effect of floor heating on thermal stratification in a single zone with a cold wall**

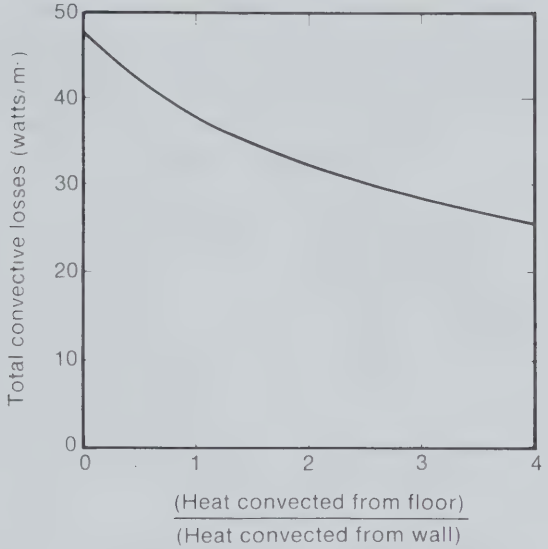


Figure 12. **Effect of floor heating on convective coupling to a cold vertical surface**

Effects of Surface Roughness

Room surfaces can have uniformly distributed roughness elements, as in the case of a masonry wall, or can have isolated projections due to window sills, door soffits, or ceiling beams. Anderson and Bohn (1984) examined the effect of distributed roughness elements on heat transfer from a vertical wall. They found the roughness elements were most effective on an isothermal wall, producing an average increase in total heat transfer of 10% to 15% and a local increase of as much as 40%.

The influence of the roughness elements on the onset of transition to turbulent flow is shown in Figures 13 and 14 for isothermal and constant flux thermal boundary conditions. The roughness caused the boundary layers to undergo transition slightly sooner than they would on a smooth surface. The boundaries of the cross-hatched area on Figure 14 are the locations of transition measured by Jaluria and Gebhardt (1974) on a vertical plate in an unconfined medium. The solid lines on Figures 13 and 14 indicate the location of transition in the absence of roughness. It can be seen from Figure 14 that transition in enclosures with heated and cooled vertical walls is delayed by about an order of magnitude as compared to transition on

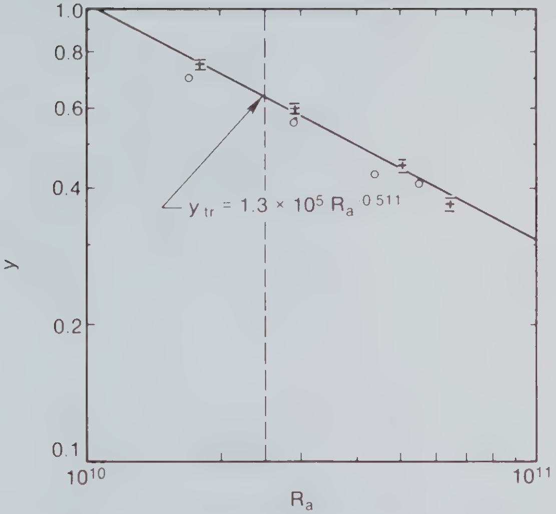


Figure 13. Effect of surface roughness on onset of transition from laminar to turbulent flow for an isothermal wall boundary condition
O = rough surface $\overline{\underline{+}}$ = smooth surface (lines above and below are error bars; solid line indicates the location of transition in the absence of roughness)

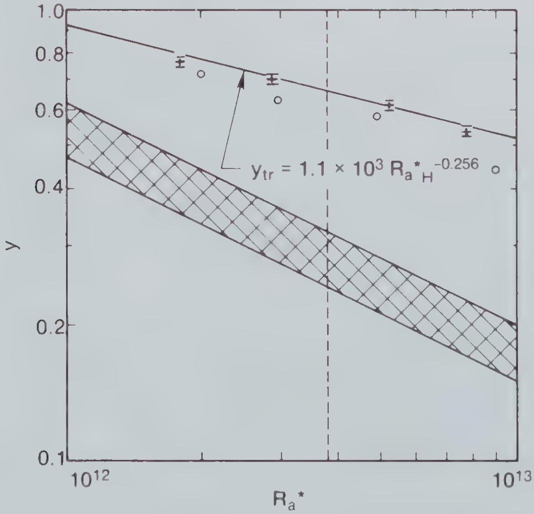


Figure 14. Effect of surface roughness on onset of transition from laminar to turbulent flow for a constant flux wall thermal boundary condition
0 = rough surface $\overline{\underline{+}}$ = smooth surface (lines above and below are error bars; boundaries of cross-hatched area are the locations of transition measured by Jaluria and Gebhardt (1974) on a vertical plate in an unconfined medium; solid line indicates the location of transition in the absence of roughness)

an isolated vertical surface. The primary reason for this delay in transition is the large level of thermal stratification in the core of the enclosure flow. This thermal stratification stabilizes the boundary layer by reducing the buoyancy force when compared to an external flow in isothermal surroundings.

Finite size roughness elements in natural convection flows have been considered by Nansteel and Greif (1984); ElSherbiny, Hollands, and Raithby (1978); Al-Arabi and El-Rafaee (1978); and Shakerin, Bohn, and Loehrke (1986). Nansteel and Greif examined downward projections similar to door soffits and found regions of intense turbulence downstream of the projection at $Ra_L = 10^{11}$. These turbulent regions did not exist if the projection extended across the entire width of the enclosure. ElSherbiny, Hollands, and Raithby considered an enclosure with one V-corrugated and one flat surface. They found heat transfer to increase by up to 50% over that for an enclosure with two smooth surfaces. Al-Arabi and El-Rafaee studied natural convection from an isolated V-corrugated plate. They compared the heat transfer results of the V-corrugated plate to a finned plate and found that the corrugated plate provided higher heat transfer than a finned plate with a weight that equalled the weight of the V-corrugated plate. Shakerin, Bohn, and Loehrke experimentally and numerically studied the changes in heat transfer produced by horizontal rectangular fins attached to a vertical heated wall in an enclosure. They found that even a perfectly conducting fin did not produce a significant increase in convective heat transfer. When the spacing between the fins was reduced below the height of the fins, they found the flow was far less able to penetrate the space between the fins. The surface heat flux in the stagnant region between closely spaced fins was reduced so that even though the total surface area of the finned wall was larger than that of a smooth wall, the total heat convective transfer rate was nearly the same.

Triangular Enclosures

Most of the natural convection studies applicable to building heat transfer have been on rectangular enclosures. Triangular spaces can occur in A-frames, rooms with clerestories, and rooms with vaulted ceilings. Flack, Konopnicki, and Rooke (1979); Flack (1980); and Poulikakos and Bejan (1983a) have conducted experimental studies of triangular enclosures. In addition, Akinete and Coleman (1982) and

Poulikakos and Bejan (1983b) have conducted numerical studies of natural convection in triangular enclosures.[5]

NATURAL CONVECTION HEAT TRANSFER BETWEEN BUILDING ZONES

Heat transfer between rooms in passive solar buildings is caused almost entirely by natural convection when the area of the flow connection or doorway is much smaller than the overall cross-sectional area of the room. Two major mechanisms can be responsible for natural convection flow between building zones:

(1) bulk density differences created by air temperature differences between hot and cold zones and

(2) thermosiphon "pumping" produced by the boundary layers that form next to heated and cooled surfaces.

Natural convection flows in solar buildings generally result from a combination of boundary layer flows and bulk density differences.

Flows Driven by Bulk Density Differences

Studies that examine flow driven by bulk density differences include those of Emswiler (1926), Brown and Solvason (1962), and Graf (1964). Emswiler calculated the flow between zones for a partition with multiple openings by using Bernoulli's equation but did not treat the heat transfer aspects of the problem. Brown and Solvason measured heat transfer in an air-filled enclosure that was divided into hot and cold regions by a single partition with a variable size opening. Using inviscid calculations and assuming isothermal fluid reservoirs on either side of the partition, they predicted that heat transfer through the partition would be correlated by a relationship of the form

$$\mathrm{Nu} = \frac{C}{3} \left(\frac{w}{W}\right) \left(\frac{h}{H}\right)^{3/2} (\mathrm{Ra}\ \mathrm{Pr})^{1/2} . \qquad (13)$$

The constant C appearing in Equation 13 is the discharge coefficient for the aperture and has values C ≥ 0.6 for high flow rates (Lienhard and Lienhard, 1984). Balcomb, Jones, and Yamaguchi (1984) recommend the value C = 0.611. Kirkpatrick, Hill, and Burns (1986) found values of $0.65 \leq C \leq 0.75$, based on measurements taken in a full-scale building. The parameters h/H and w/W that appear in Equation 13 are the ratios of doorway height to total room height and doorway width to room width, respectively. The temperature difference used in the definition of Nu and Ra in Equation 13 is the temperature difference between the fluid in the hot and cold zones.

Graf used inviscid calculations to examine mixed forced and free convection flow by adding the pressure contribution from the forced flow to the pressure difference produced by the density differences between the fluid reservoirs. Figure 15 demonstrates the types of flow profiles that result from the inviscid calculations. Balcomb and Yamaguchi (1983) have demonstrated that skew velocity profiles similar to Figure 15 can also occur in multilevel passive solar buildings without the presence of a forced flow because of the complex flow paths created by hallways, stairways, and doors.

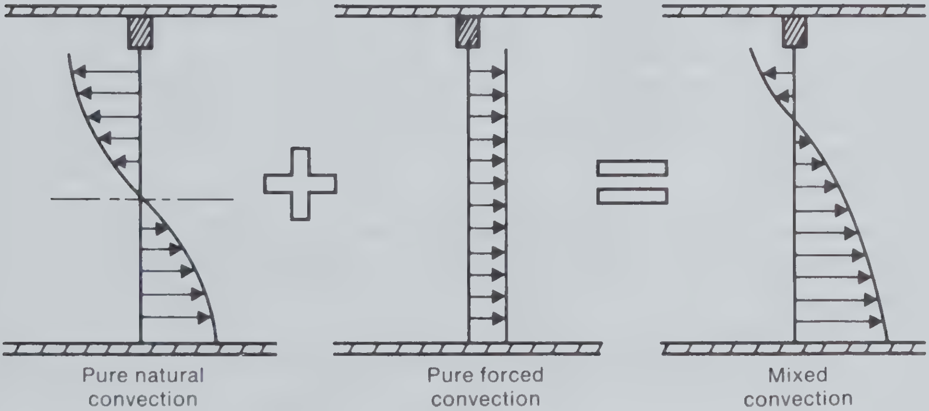


Figure 15. Interzone flow profiles predicted by using Bernoulli's equation and assuming isothermal fluid reservoirs on either side of the partition. The combination of a forcing pressure in addition to the density difference between the fluid reservoirs produces a skewed velocity profile.

Flows Driven by Boundary Layer Pumping

Many quantitative studies have been done of simple interzonal natural convection flows for the case when the flow between zones is driven entirely by boundary layers. Two-dimensional partitions have been considered by Janikowski, Ward, and Probert (1978); Bejan and Rossie (1981); Nansteel and Greif (1981 and 1984); Bajorek and Lloyd (1982); Chang, Lloyd, and Yang (1982); and Lin and Bejan (1983). All these studies were experimental except that of Chang, Lloyd, and Yang, which was a finite difference model of a geometry similar to the experimental work of Bajorek and Lloyd. Lin and Bejan provide a perturbation solution valid in the limit $Ra \to 0$ in addition to their experimental results. The only three-dimensional study is that of Nansteel and Greif, who consider a partition with a rectangular opening. Figure 16 summarizes these papers. An interesting result of these studies is that a partition tends to damp out the flow in subregions that are subjected to stable thermal boundary conditions. This effect reduces the effective wall area exposed to the primary flow, as can be seen in the flow patterns observed by Bejan and Rossi, Nansteel and Greif, and Lin and Bejan. This reduction in actively participating surface area produces a proportional reduction in heat transfer when compared to an enclosure without intervening partitions. The reduction also leads to the formation of a relatively hot, stagnant layer of air near the ceiling of a sunspace if the height of the sunspace is larger than the height of the sunspace doorway.

Nansteel and Greif recommend the following relation for boundary-layer-driven heat transfer through a simple partition separating two rooms:

$$Nu = 0.915\ (h/H)^{0.401}\ Ra^{\ 0.207} \tag{14}$$

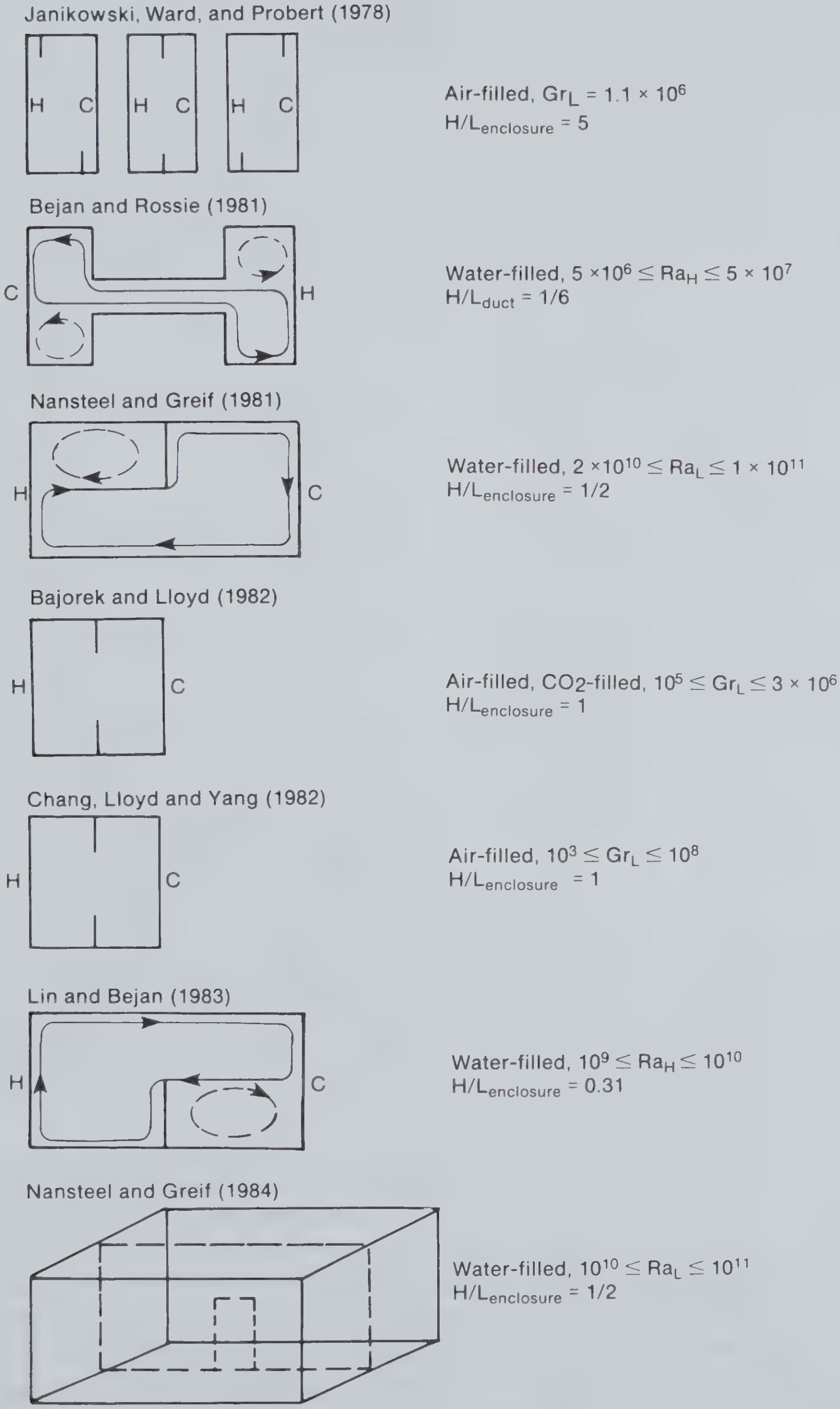
for

$$1/4 \le h/H \le 1 \tag{15}$$

and

$$w/W \ge 0.093\ . \tag{16}$$

The temperature difference used in the evaluation of Nu and Ra in Equation 14 is the temperature difference between the hot and cold end walls of the enclosure.


Janikowski, Ward, and Probert (1978)

Air-filled, $Gr_L = 1.1 \times 10^6$
$H/L_{enclosure} = 5$

Bejan and Rossie (1981)

Water-filled, $5 \times 10^6 \leq Ra_H \leq 5 \times 10^7$
$H/L_{duct} = 1/6$

Nansteel and Greif (1981)

Water-filled, $2 \times 10^{10} \leq Ra_L \leq 1 \times 10^{11}$
$H/L_{enclosure} = 1/2$

Bajorek and Lloyd (1982)

Air-filled, CO_2-filled, $10^5 \leq Gr_L \leq 3 \times 10^6$
$H/L_{enclosure} = 1$

Chang, Lloyd and Yang (1982)

Air-filled, $10^3 \leq Gr_L \leq 10^8$
$H/L_{enclosure} = 1$

Lin and Bejan (1983)

Water-filled, $10^9 \leq Ra_H \leq 10^{10}$
$H/L_{enclosure} = 0.31$

Nansteel and Greif (1984)

Water-filled, $10^{10} \leq Ra_L \leq 10^{11}$
$H/L_{enclosure} = 1/2$

Figure 16. Summary of interzone natural convection studies

Studies Conducted in Full-Scale Buildings

Studies of natural convection flows in full-scale buildings have been reported by Shaw (1971); Balcomb and Yamaguchi (1983); Balcomb, Jones, and Yamaguchi (1984); and Kirkpatrick, Hill, and Burns (1986). Shaw included the effects of forced air flow. Kirkpatrick, Hill, and Burns included these effects as well as examined the effect of thermal stratification on the flow between zones. Owing to the relatively low level of thermal stratification measured during their experiment, Kirkpatrick, Hill, and Burns found only a small difference between predictions based on stratified and isothermal models. Shaw and Kirkpatrick, Hill, and Burns conducted their measurements in an unoccupied building. Balcomb and Yamaguchi, and Balcomb, Jones, and Yamaguchi conducted measurements in a series of occupied houses encompassing a wide range of floor plans. Balcomb (1985) summarizes the results of these experiments.

These full-scale studies demonstrate that the bulk density model can be used to describe air flow between zones with large air temperature differences. Some disagreement exists concerning the correct temperature difference for Equation 13. Shaw used the temperature difference between the top and bottom of the doorway. Kirkpatrick, Hill, and Burns integrated the temperature difference measured at equal heights on either side of the doorway. Balcomb, Jones, and Yamaguchi used the temperature difference at midheight on either side of the doorway, with a correction factor to account for the difference between the room-to-room temperature difference and the temperature difference between the top and bottom of the doorway. Experiments conducted in scale-model test cells by Weber and Kearney (1980) and Yamaguchi (1984) have examined the effects of various definitions of zone-to-zone temperature difference on the heat transfer results.

Jones, Balcomb, and Otis (1985) have developed a model for air transport in a two-zone enclosure with heated and cooled end walls similar to Figure 3b. The model incorporates features found from observations made in more than 12 full-scale buildings. Jones, Balcomb, and Otis found that sunspace glazing in direct sun is typically about 5°C (10°F) warmer than the sunspace air. This temperature difference was found to produce a strong upward boundary-layer flow on the glazing, which entrains cool air from the sunspace core. Jones, Balcomb, and Otis measured velocities of 0.46 to 0.61 m/s (1.5 to 2.0 ft/s) in the glazing boundary layer and estimated that the sunspace glazing accounted for more than half of the heat flow from the sunspace into the remainder of the building during periods of strong solar heating. Their model couples the boundary layers that form on the heated and cooled end walls with a bulk density model for the flow through the aperture separating the hot and cold zones. Initial use of the model has been limited to the study of the transient flow that results when the door separating the hot and cold zones is suddenly opened.

Blockage of Boundary-Layer Flows

A comparison of Equations 13 and 14 demonstrates that the natural convection flow regime that governs the flow through the aperture (bulk-density driven or boundary-layer driven) strongly affects the geometric dependence of the heat transfer coefficient. In the bulk-density-driven regime (Equation 13), the heat transfer coefficient depends strongly on both the aperture height ratio h/H and the aperture width ratio w/W. In the boundary-layer-driven regime (Equation 14), the heat transfer coefficient depends weakly on the aperture height ratio and appears to be independent of the aperture width ratio. Because of these differences, one must be able to predict when a multizone flow is in the bulk-density-driven or boundary-layer-driven regime.

Nansteel and Greif (1984) have demonstrated that heat transfer between two zones in the boundary layer regime is nearly independent of the width of the aperture between zones for $w/W \geq 0.093$ and $0.25 \leq h/H \leq 1.0$. However, as the width of the aperture is reduced, the boundary layer flow will eventually be blocked. Flow blockage will result in the formation of large temperature differences across the aperture and cause a transition from boundary-layer-driven to bulk-density-driven convection.

The onset of boundary-layer flow blockage can be estimated by comparing the total cross-sectional area required by the boundary-layer flow to the area of the aperture between zones. If the aperture is smaller than the area required by the boundary-layer flow, then it will have to accelerate to pass through the aperture. The additional driving force required to convect the flow through the aperture can only be provided by the creation of bulk density differences between the hot and cold zones of the enclosure.[6]

Scott, Anderson, and Figliola (1985) conducted an experimental investigation to determine the onset of blockage of natural convection boundary-layer flow in a two-zone cavity with differentially heated end walls. They varied the width of the aperture between the zones while measuring the heat transfer and temperature distributions within the cavity. Figure 17 shows the temperature difference between the hot and cold zone measured by Scott, Anderson, and Figliola as a function of the size of the aperture between zones, for a constant level of convective energy transport between zones. The temperature difference required to transport an equivalent amount of energy using bulk density differences is also shown in Figure 17, as calculated from Equation 13.

Scott, Anderson, and Figliola found that the boundary-layer flow studied during their experiment required a smaller zone-to-zone temperature difference than a flow driven by bulk density differences provided that the area of the flow aperture was larger than 2% of the total cross-sectional area of the enclosure. This result

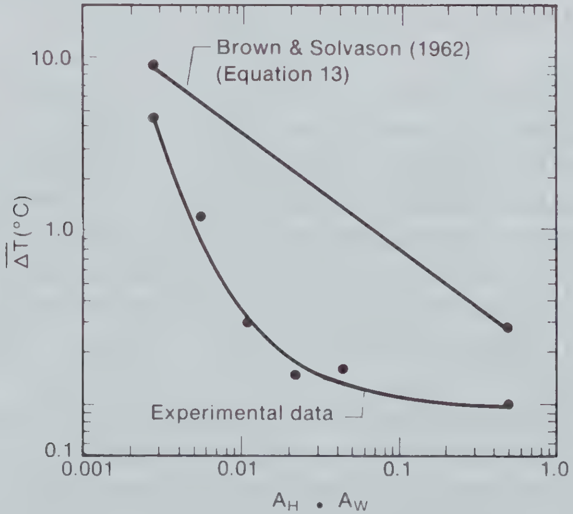


Figure 17. **Temperature difference between hot and cold zones measured by Scott et al. (1985) shown as a function of aperture area.**
$\overline{\Delta T}$ = fluid temperature difference between hot and cold zones.

suggests that substantial benefits can be associated with the use of boundary layer flows, particularly in retrofit applications where flow aperture areas are limited.

Trombe Walls and Thermosiphoning Air Panels

The two-zone studies described above assumed that the zones on either side of the dividing partition have aspect ratios of order one. In Trombe walls and thermosiphoning air panels, the width of the direct-gain zone is reduced until it becomes a vertical duct bounded by the window surface and the absorbing wall surface.[7]

Sparrow and Azevedo (1985) experimented with the effect of channel width on natural convection heat transfer between vertical parallel plates. They found that heat transfer was reduced dramatically if the width of the channel had the same order of magnitude as the boundary-layer thickness. The reduction in convection heat transfer measured during their experiment is plotted as a function of channel spacing in Figure 18. Sparrow and Azevedo were able to

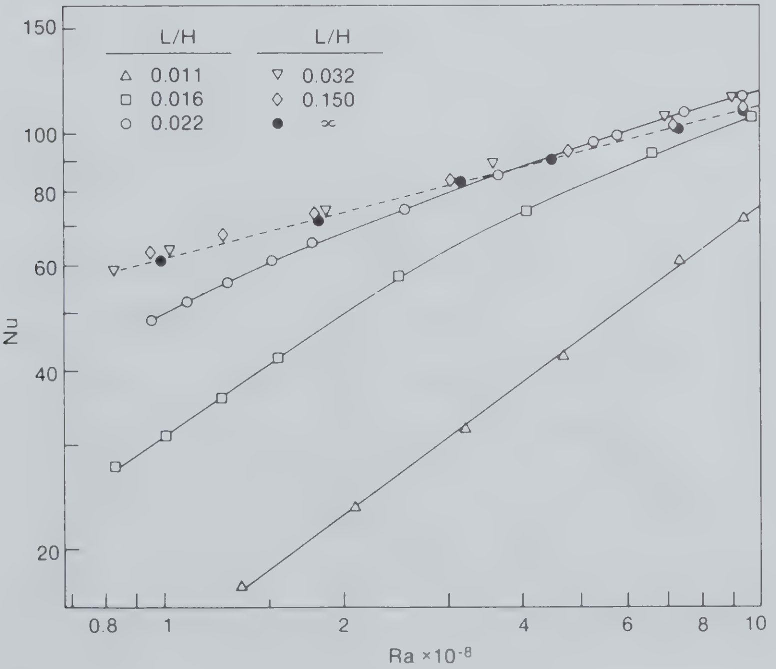


Figure 18. Effect of spacing on heat transfer in a parallel plate channel

reduce all their data to a single curve by plotting the data as shown in Figure 19. Their final correlation for heat transfer over the entire range of plate spacing $0.011 \le L/H \le 0.5$ is

$$Nu_L = \{ (\frac{12}{L/H\ Ra_L})^2 + (\frac{1}{0.619\ (L/H\ Ra_L)^{1/4}})^2 \}^{-1/2} . \quad (17)$$

To avoid blockage of the flow through the duct, Sparrow and Azevedo found that the channel width should satisfy the following inequality, for a channel that was heated along one wall:

$$L/H\ Ra^{1/4} \geq 5 . \quad (18)$$

For Trombe wall and thermosyphoning air panel applications where heating occurs on both walls, this guidance should be multiplied by a factor of two:

$$L/H\ Ra^{1/4} \geq 10 . \quad (19)$$

For a Trombe wall with $Ra = 10^{10}$ and H = 2.4 m (8 ft), Equation 19 gives a recommended Trombe wall channel spacing of

$$L \geq 3 \text{ in.} \quad (20)$$

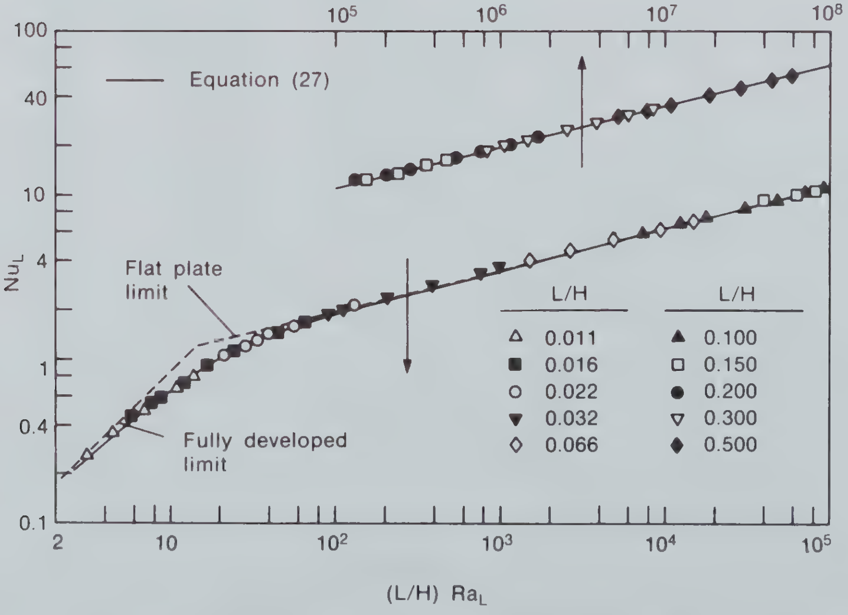


Figure 19. Heat transfer in a parallel plate channel

Sparrow and Azevedo did not examine the effect of entrance and exit losses during their study; therefore, Equations 18 and 19 should not be used to size entrance and exit apertures for Trombe wall and thermosiphoning air-panel applications.

Recommendations for Future Research

A preliminary understanding has been developed of the factors that govern natural convection transport in solar buildings. However, several applied and fundamental research areas still require further work:

a) Advanced building materials. The development of advanced building materials, such as fenestrations with switchable transmissivities and drywall incorporating phase-change thermal-storage materials, promises to give the thermal designer tremendous control over the distribution of solar gains and the placement of thermal storage in solar buildings. A critical need exists for the development of design guidelines to ensure that the performance of these advanced materials is not limited by heat transfer. Phase-change drywall will not perform well if convective coupling is inadequate. Many of the switchable fenestrations can be highly absorptive and may cause overheating in some applications.

b) Mixed forced/free convection in solar building components. Natural convection is an effective mechanism for energy transport in solar buildings. However, performance can be improved by using forced flows to aid natural convection. The performance of many hybrid solar building systems has been disappointing (Balcomb, 1985). Comprehensive design guidelines are needed for sizing of apertures, fans, and baffles in hybrid solar building components such as wall-attached air panels and hot-air redistribution systems. In addition, convective coupling to thermal storage in ventilation cooling applications is not well understood. A recent study by Johnson, Neiswanger, and Casey (1986) demonstrates that the level of convective coupling can vary by as much as a factor of three, depending on the location on the thermal storage wall.

c) Thermal stratification and overheating in atria and sunspaces. Overheating reduces thermal comfort and increases thermal losses in solar buildings. Well-designed sunspaces are generally only 25% efficient. Daylighting in large atria can result in excess solar gains that must be removed by increasing the capacity of the HVAC system. Additional study is required to improve the thermal performance of atria and sunspaces by increasing our understanding of the mechanisms that produce thermal stratification and overheating problems.

d) Boundary layer energy transport. Preliminary research results suggest that multizone flows driven by boundary layers will not be blocked as long as the flow aperture area is not reduced below 2% of the solar aperture area. Design guidelines based on bulk-density driven flow suggest that the flow aperture area should not be reduced below 15% of the solar aperture area. The smaller aperture areas required by boundary layer flows can provide additional architectural freedom, particularly in retrofit applications where flow aperture area may be limited. Additional research is necessary to provide design guidelines for the use of boundary layer transport in multizone building flows.

A substantial level of research effort is currently being conducted in the areas described above by solar researchers as well as by researchers in the related fields of smoke and fire spread, indoor air quality, and cooling of electronic equipment. The widespread use of microcomputers should make it fairly easy to adapt the thermal design algorithms developed by these researchers into a form that can be easily used by architects, builders, and designers.

NOTES

---

[1] The radiation heat loss has been calculated by assuming that the window and room can be modeled as ideal black surfaces. The radiative heat transfer coefficient $\bar{h}_{rad}$ used in Figure 5 is defined as:

$$\bar{h}_{rad} = \sigma \frac{(T_H^4 - \bar{T}_{Window}^4)}{(T_H - T_C)} \qquad (21)$$

where σ is the Stefan-Boltzman constant and $\bar{T}_{window}$ is the average temperature of the window surface. T_H is the internal (hot) temperature, and T_C is the external (cold) temperature. For the case of zero external wind the average window temperature is

$$\bar{T}_{window} = \frac{(T_H + T_C)}{2} \,. \tag{22}$$

For the case of high external wind it was assumed that

$$\bar{T}_{window} = T_C. \tag{23}$$

The internal temperature T_H is assumed to be constant at 20°C (68°F). The natural convection heat transfer coefficient used in Figure 5 for the case of zero external wind is based on the conjugate conductive/convective analysis of Anderson and Bejan (1980 and 1981). The natural convection heat transfer coefficient used in Figure 5 for the case of high external wind is based on the boundary layer analysis of Gill (1966) and Bejan (1979) under the assumption that the window surface temperature approaches the external air temperatures.

[2] The constant height H/variable spacing L case considered by Korpela, Lee, and Drummond (1982) is distinct from the constant L/variable H case previously considered by Bejan (1980). Bejan's analysis assumes boundary layer flow and considers the dependence of Nu_L on aspect ratio with fixed plate spacing L and variable height H. Korpela, Lee, and Drummond limit their study to the consideration of Ra numbers in the transitional region between conduction- and boundary-layer-dominated heat transfer and consider the dependence of Nu on aspect ratio with fixed H and variable L. Their results can be used to determine the Ra,A combination, which produces minimum heat transfer at fixed H, while Bejan's analysis allows one to determine the Ra_L,A combination producing maximum heat transfer at fixed L.

[3] If this scaling is not observed, the heat transfer from a vertical surface in an enclosure with complicated boundary conditions on its vertical walls can appear to be drastically different from that in an enclosure where one vertical surface is uniformly heated and one vertical surface is uniformly cooled. For example, in a cubical enclosure with four vertical walls, three hot (T_H) and one cold (T_C), the bulk temperature difference for the cold wall is

$$\Delta T_b = \frac{\Delta T}{4} \tag{24}$$

where

$$\Delta T = T_H - T_C. \tag{25}$$

The overall heat transfer to the cold wall has to be the same regardless of the temperature difference used in the definition of the heat transfer coefficient. This implies that

$$\bar{h}_b \, \Delta T_b = \bar{h} \, \Delta T \tag{26}$$

or

$$\frac{\bar{h}}{\bar{h}_b} = \frac{\Delta T_b}{\Delta T} = \frac{1}{4} \, . \qquad (27)$$

Equation 27 indicates that the heat transfer coefficient based on ΔT will be four times smaller than the heat transfer coefficient based on ΔT_b for the three-heated and one-cooled wall geometry described above. This apparent discrepancy is a result of the choice of the temperature difference used in the definition of the heat transfer coefficient and does not indicate a drastic change in the convective heat transfer mechanism. If ΔT_b is used rather than ΔT, the heat transfer coefficient does not change significantly regardless of the thermal boundary conditions on the vertical walls of the enclosure.

---

[4] Ostrach and Raghavan (1979) studied the configuration CHHC for high Prandtl silicone oils in enclosures with aspect ratios of one and three. Here H refers to a heated wall and C refers to a cooled wall. The notation scheme begins with the floor, the righthand vertical side wall, the top, and then the lefthand vertical side wall. The two remaining vertical side walls were insulated. Ostrach and Raghavan found that heating of the top wall and cooling of the bottom wall reduced the vertical velocity near the vertical wall. Fu and Ostrach (1981) examined the same heating configuration as Ostrach and Raghavan but considered the effect of symmetric as well as asymmetric heating. Symmetric heating occurs when $(T_T + T_B)/2 = (T_H + T_C)/2$. They found that the symmetrical case produced the greatest reduction in the vertical velocity. Shiralkar and Tien (1982) conducted numerical studies of stable and unstable heating corresponding to configurations CHHC and HHCC. Shiralkar and Tien did not observe any thermal instabilities such as Benard cells or thermal plumes when the enclosure was subjected to unstable heating (configuration CHHC), but the temperature distribution in the core was found to be strongly dependent on the heating configuration. Stable heating (configuration HHCC) produced a motionless core with a high level of thermal stratification. Unstable heating induced motion in the core, making it almost isothermal. Kirkpatrick and Bohn (1983 and 1986) conducted a series of experiments in a water-filled cubical enclosure that was heated from below while the thermal boundary conditions on two side walls and the top wall of the enclosure were varied. Kirkpatrick and Bohn tested three configurations: HHCC, HHHC, and HCCC. They conducted their study at Rayleigh numbers four orders of magnitude higher than any previous studies. They found the thermal boundary condition on the top wall of the enclosures to strongly influence the temperature distribution and flow structure in the enclosure. When both the floor and the ceiling were heated, they found the fluid in the core was highly stratified. When the floor was heated and the ceiling was cooled, turbulent thermal plumes were generated at the top and bottom surfaces of the enclosure and the thermal stratification of the core was destroyed.

[5] Flack, Konopnicki, and Rooke measured the heat transfer in an air-filled isosceles triangular enclosure by using an interferometer. The base of the enclosure was insulated and the enclosure had one isothermal-heated and one isothermal-cooled upper wall. Flack, Konopnicki, and Rooke found the average Nusselt number to be within 10% to 20% of the values for a rectangular enclosure but found a strong conduction-dominated region near the apex of the enclosure because of the physical proximity of the hot and cold surfaces in that region. This conduction-dominated region caused a sharp increase in heat transfer on the hot wall near the apex.

Flack used the same apparatus previously used by Flack, Konopnicki, and Rooke to examine the case when both of the upper sides of the enclosure were the same temperature while the floor of the enclosure was maintained at a different temperature. For stable heating (hot ceiling-cold floor), the heat transfer varied at most by 10% from a pure conduction solution. Four horizontally aligned Benard cells formed along the long axis of the enclosure during unstable heating (hot base-cold sides). The axis of rotation of the Benard cells was perpendicular to the long axis of the enclosure. Poulikakos and Bejan considered natural convection in an air-and-water filled, unstably heated, right triangular enclosure. The flow was found to be turbulent during the water experiments owing to the higher Rayleigh numbers that were achieved in their apparatus.

Akinete and Coleman conducted a numerical study on a stably heated, right triangular enclosure for the range $800 \le Gr_L \le 6400$, $0.0635 \le A \le 1$ and $Pr = 0.733$. They found a drastic drop in heat transfer as the aspect ratio was increased, indicating that the heat transfer process was conduction dominated. The same conduction-dominated behavior was observed by Flack in stably heated, isosceles triangular enclosures. Poulikakos and Bejan conducted a two-dimensional transient numerical study of an isosceles triangular enclosure with cold upper sides and a warm base. Their calculation assumed that the fluid in the enclosure was initially isothermal at the base temperature T_H. At time $t = 0$ the upper sides of the enclosure were suddenly cooled to T_C. For high-aspect ratio enclosures the transient Nusselt numbers initially overshot their steady-state values. The numerical solution of Poulikakos and Bejan assumed two symmetrical axially oriented rolls in contrast to the transversely oriented rolls observed by Flack.

[6] The flow area A_{bl} required by the boundary layers on heated and cooled surfaces can be calculated by summing the product of the thickness and width of each boundary layer in the enclosure:

$$A_{bl} = \sum_{n=1}^{N} (\delta W)_n \ . \tag{28}$$

According to the model described above, flow blockage will occur when

$$\frac{A_{bl}}{\ell w} = \frac{\sum_{n=1}^{N} (\ell W)_n}{\ell w} \sim 1 \ . \tag{29}$$

For laminar flow the natural convection boundary-layer thickness next to a vertical surface is scaled by the relationship (Bejan, 1984)

$$\frac{\delta}{H} \sim \frac{1}{Ra_H^{*1/5}} \ . \tag{30}$$

If we assume that the height, width, and average heat flux from each active surface are the same, with the values H, W, and q", respectively, then the flow blockage criteria expressed by Equation 29 can be rearranged into the simple form

$$\frac{h}{H} \cdot \frac{w}{W} \sim \frac{N}{Ra_H^{*1/5}} \ . \tag{31}$$

The quantity Ra_H^*, which appears in Equations 30 and 31, is the flux modified Rayleigh number and is defined by Equation 2. The lefthand side of Equation 31 is the ratio of the area of the aperture to the cross-sectional area of the room, and N is the number of active heat transfer surfaces in the room. Equation 31 predicts that the onset of flow blockage is directly proportional to the number of active heat transfer surfaces and is inversely proportional to the Rayleigh number, which characterizes the natural convection flow. In simple terms, Equation 31 predicts that a small volume of hot air is less subject to flow blockage than a large volume of warm air.

[7] Elenbaas (1942) and Ostrach (1952) performed the first studies of natural convection in the duct formed by two vertical parallel surfaces. Studies with specific applications to solar buildings have been done by Akbari and Borgers (1979); Allen and Hayes (1985); Tasdemiroglu, Berjano, and Tinaut (1985); and Ormiston, Raithby, and Hollands (1985). Bodoia and Osterle (1962) considered the problem of developing flow between two isothermal plates with the same temperature. Miyatake and Fujii (1972) and Miyatake, Fujii, Fujii, and Tanaka (1973) calculated developing flow between two vertical plates when one plate was insulated and the other was an isothermal or constant flux surface. Aung, Fletcher, and Sernas (1972) conducted a numerical and experimental investigation of developing natural convection flow in a vertical duct with asymmetric side-wall heating for both constant heat flux and constant temperature boundary conditions. Kettleborough (1972) used an elliptic calculation method and found that regions of reverse flow could exist, particularly at high Rayleigh numbers. Sparrow, Chrysler, and Azevedo (1984) observed flow reversals near the exit of a vertical channel with one insulated side wall and one isothermal side wall, but found that the average Nusselt number was unaffected by the presence of the recirculating zone. Sparrow, Shah, and Prakash (1980) considered natural convection combined with radiation in a vertical channel with one insulated wall and one isothermal wall. They found that the radiative transport between the walls increased the convective heat transfer by 50% to 70% for $1.1 \le T_W/T_\infty \le 1.25$.

NOMENCLATURE

A = aspect ratio, H/L

B = constant vertical temperature gradient in tall vertical slot

Bi = wall Biot Number, $\frac{k_w t}{k_f H}$

c_p = specific heat at constant pressure

h = doorway height

$\bar{h}$ = convective heat transfer coefficient, $\frac{q}{HL\Delta T}$

H = enclosure height

L = spacing between enclosure walls

Pr = Prandtl Number, $\frac{\mu c_p}{k}$

q = total heat transfer across cavity

T = temperature

ΔT = $T_H - T_C$

α = thermal diffusivity, $\frac{k}{\rho c_p}$

ν = kinematic viscosity, $\frac{\mu}{\rho}$

μ = viscosity

Subscripts

b = bulk value

B = bottom wall

BL = boundary layer

C = cold vertical wall or cold fluid reservoir

DR = doorway

H = hot vertical wall or hot fluid reservoir

L = based upon the length scale L

rad = radiation

tr = location of transition

T = top

u = horizontal component of velocity

v = vertical component of velocity

x = horizontal distance or coordinate

y = vertical distance or coordinate

Ra = Rayleigh Number, $\frac{g\beta H^3 \Delta T}{\nu\alpha}$

Ra* = modified Rayleigh Number, $\frac{g\beta H^4 q''}{\nu\alpha R}$

Nu = Nusselt Number, $\frac{hH}{k}$

Greek

β = coefficient of thermal expansion

σ = Stephan-Boltzman constant

δ = boundary layer thickness

REFERENCES

Akbari, H., and T.R. Borgers, 1979. Free convective laminar flow within the Trombe wall channel. Solar Energy 22:165-174.

Akinete, V.A., and T.A. Coleman, 1982. Heat transfer by steady laminar free convection in triangular enclosures. Int. J. Heat Mass Transfer 25: 991-998.

Al-Arabi, M., and M.M. El-Rafaee, 1978. Heat transfer by natural convection from corrugated plates to air. Int. J. Heat Mass Transfer 21:357-359.

Allen, T., and J. Hayes, 1985. Measured performance of thermosiphon air panels. In Proc. of the 10th National Passive Conf. Boulder, CO: ASES. pp. 442-447.

Altmayer, E.F., A.J. Gadgil, F.S. Bauman, and R.L. Kammerud, 1983. Correlations for convective heat transfer from room surfaces. ASHRAE Transactions 89:Part 2A, 61-77.

Anderson, R., and A. Bejan, 1980. Natural convection on both sides of a vertical wall separating fluids at different temperatures. J. Heat Transfer 102:630-635.

Anderson, R., and A. Bejan, 1981. Heat transfer through single and double vertical walls in natural convection: theory and experiment. Int. J. Heat Mass Transfer 24:1611-1620.

Anderson, R., and M. Bohn, 1984. Heat transfer enhancement in natural convection enclosure flow. ASME Winter Annual Meeting, New Orleans.

Anderson, R., E.M. Fisher, and M. Bohn, 1985a. Natural Convection in a Closed Cavity with Variable Heating of the Floor and One Vertical Wall. SERI/PR-252-2591, Golden, CO: SERI.

Anderson, R., E. Fisher, and M. Bohn, 1985b. Thermal Stratification in Direct Gain Passive Heating Systems with Variable Heating of the Floor and One Vertical Wall. SERI/TP-252-2767, Golden, CO: SERI.

Anderson, R., and G. Lauriat, 1986. The horizontal natural convection boundary layer regime in a closed cavity. In Proc. of 8th Int. Heat Transfer Conf., San Francisco, CA.

Aung, W., L.S. Fletcher, and V. Sernas, 1972. Developing laminar free convection between vertical flat plate with asymmetric heating. Int. J. Heat Mass Transfer 15:2293-2308.

Bajorek, S.M., and J.R. Lloyd, 1982. Experimental investigation of natural convection in partitioned enclosures. J. Heat Transfer 104:527-532.

Balcomb, J.D., 1981. Passive solar energy systems for buildings. Solar Energy Handbook, Jan F. Kreider and Frank Kreith, eds. New York: McGraw-Hill, pp. 16-27.

Balcomb, J.D., 1985. Heat Distribution by Natural Convection: Interim Report. Los Alamos, NM: Los Alamos National Laboratory.

Balcomb, J.D., G.F. Jones, and K. Yamaguchi, 1984. Natural convection airflow measurement and theory. In Proc. of Ninth National Passive Solar Conf., Columbus, OH. Boulder, CO: ASES.

Balcomb, J.D., and K. Yamaguchi, 1983. Heat distribution by natural convection. In Proc. of the 8th National Passive Solar Conf., Santa Fe, NM. Boulder, CO: ASES.

Balvanz, J.L., and T.H. Kuehn, 1980. Effect of wall conduction and radiation on natural convection in a vertical slot with uniform heat generators on the heated wall. Natural Convection in Enclosures, ASME HTD 8:55-62.

Barakat, S.A., 1985. Inter-zone convective heat transfer in buildings: a review. In Heat Transfer in Buildings and Structures. P.J. Bishop, ed., ASME HTD 41:45-52.

Bauman, F., A. Gadgil, R. Kammerud, E. Altmayer, and M. Nansteel, 1983. Convective heat transfer in buildings: recent research results. ASHRAE Transactions 89:Part 1A, 215-230.

Bejan, A., 1979. Note on Gill's solution for free convection in a vertical enclosure. J. Fluid Mech. 90:561.

Bejan, A., 1980. A synthesis of analytical results for natural convection heat transfer across rectangular enclosures. Int. J. Heat Mass Transfer 23(5):723-726.

Bejan, A., 1984. Convection Heat Transfer. New York: John Wiley & Sons. p. 116.

Bejan, A., and A.N. Rossie, 1981. Natural convection in horizontal duct connecting two fluid reservoirs. J. Heat Transfer 103:108-113.

Bejan, A., and C.L. Tien, 1978. Laminar natural convection heat transfer in a horizontal cavity with different end temperatures. J. Heat Transfer 100C, 641.

Bodoia, J.R., and J.F. Osterle, 1962. The development of free convection between heated vertical plates. J. Heat Transfer 85:40-44.

Bohn, M.S., and R. Anderson, 1984. Influence of Prandtl Number on Natural Convection Heat Transfer Correlations. SERI/TR-252-2067, Golden, CO: SERI.

Bohn, M.S., and R. Anderson, 1986. Temperature and heat flux distributing in a natural convection enclosure flow. (to appear in J. Heat Transfer).

Bohn, M.S., A.T. Kirkpatrick, and D.A. Olsen, 1984. Experimental study of three-dimensional natural convection at high Rayleigh number. J. Heat Transfer 106:339-345.

Brown, W.G., and K.R. Solvason, 1962. Natural convection through rectangular openings in partitions--1. Int. J. Heat Mass Transfer 5:859-868.

Buchberg, H., I. Catton, and D.K. Edwards, 1976. Natural convection in enclosed spaces - a review of application to solar energy collection. J. Heat Transfer 98:182-188.

Catton, I., 1978. Natural convection in enclosures. 6th International Heat Transfer Conf., National Research Council of Canada.

Chang, L.C., J.R. Lloyd, and K.T. Yang, 1982. A finite difference study of natural convection in complex enclosures. 7th Int. Heat Transfer Conf.

Chao, P.K.-B., H. Ozoe, and S.W. Churchill, 1981. The effect of a nonuniform surface temperature on laminar natural convection in a rectangular enclosure. Chem. Eng. Commun. 9:245-254.

Chapman, A.J., 1974. Heat Transfer, 3rd edition, New York: MacMillan.

Cormack, D.E., L.G. Leal, and J. Imberger, 1974. Natural convection in a shallow cavity with differentially heated end walls--Part 1. Asymptotic theory, J. Fluid Mech. 65:209.

Elder, J.W., 1965. Laminar free convection in a vertical slot. J. Fluid Mech. 23:77.

Elenbaas, W., 1942. Heat dissipation of parallel plates by free convection. Physica 9:1.

ElSherbiny, S.M., K.G.T. Hollands, and G.D. Raithby, 1978. Free convection across inclined air layers with one surface V-corrugated. J. Heat Transfer 100:410-415.

ElSherbiny, S.M., G.D. Raithby, and K.G.T. Hollands, 1982. Heat transfer by natural convection across vertical and inclined air layers. J. Heat Transfer 104:96-102.

Emswiler, J.E., 1926. The neutral zone in ventilation. Trans. Amer. Soc. Heat Vent. Eng. 32:59-74.

Flack, R.D., 1980. The experimental measurement of natural convection heat transfer in triangular enclosures heated or cooled from below. J. Heat Transfer 102:770-772.

Flack, R.D., T.T. Konopnicki, and J.H. Rooke, 1979. The measurement of natural convective heat transfer in triangular enclosures. J. Heat Transfer 101:648-654.

Fu, B-I, and S. Ostrach, 1981. The effects of stabilizing thermal gradients on natural convection flows in a square enclosure. ASME HTD 16.

Gill, A.E., 1966. The boundary-layer regime for convection in a rectangular cavity. J. Fluid Mech. 26:515-536.

Graf, A., 1964. Theoretische Betrachtung uber den Luftaustauch zwischen zwei Raumen. Schweiz. Bl. Heiz. Luft 31:22-25.

Han, J.T., 1967. M.A. Science Thesis. Department of Mechanical Engineering, University of Toronto.

Jaluria, Y., and B. Gebhardt, 1974. On transition mechanisms in vertical natural convection flow. J. Fluid Mech. 66:309-339.

Jaluria, Y., 1982. Buoyancy-induced flow due to isolated thermal sources on a vertical surface. J. Heat Transfer 104:223-227.

Janikowski, H.E., J. Ward, and S.D. Probert, 1978. Free convection in vertical, air-filled rectangular cavities fitted with baffles. 6th Int. Heat Transfer Conf., Toronto.

Johnson, G.A., L. Neiswanger, V.P. Casey, 1986. Cross-flow mixed convection at high Rayleigh number in an open-ended rectangular enclosure. To be presented at 1986 ASME Winter Annual Meeting, Anaheim, CA, December 7-12.

Jones, G.F., J.D. Balcomb, and D.R. Otis, 1985. A model for thermally driven heat and air transport in passive solar buildings. ASME 85-WA/HT-69.

Kettleborough, C.F., 1972. Transient laminar free convection between heated vertical plates including entrance effects. Int. J. Heat Mass Transfer 15:883-896.

Kirkpatrick, A.T., and M.S. Bohn, 1983. High Rayleigh number natural convection in an enclosure heated from below and from the sides. ASME-AiChE National Heat Transfer Conf., Seattle, WA.

Kirkpatrick, A.T., and M.S. Bohn, 1986. An experimental investigation of mixed cavity natural convection in the high Rayleigh number regime. Int. J. Heat Mass Transfer 29(1):69-82.

Kirkpatrick, A., D. Hill, and P. Burns, 1986. Analysis and measurement of interzonal convection (to appear in J. Solar Energy Eng.).

Korpela, S.A., Y. Lee, and J.E. Drummond, 1982. Heat transfer through a double pane window. J. Heat Transfer 104:539-544.

Kubleck, K., G.P. Marker, and J. Straub, 1980. Advanced numerical computation of two-dimensional time-dependent free convection in cavities. Int. J. Heat Mass Transfer 23:203-217.

Lienhard V, J.H., and J.H. Lienhard IV, 1984. Velocity coefficients for free jets from sharp-edged orifices. J. Fluids Eng. 106:13-17.

Lin, N.N., and A. Bejan, 1983. Natural convection in a partially divided enclosure. Int. J. Heat Mass Transfer 26:1867-1878.

Lock, G.S.H., and R.S. Ko, 1973. Coupling through a wall between two free convective systems. Int. J. Heat Mass Transfer 16:2087-2096.

MacGregor, R.K., and A.F. Emery, 1969. Free convection through vertical plane layers--moderate and high Prandtl number fluids. J. Heat Transfer 91:391-403.

Miyatake, O., and T. Fujii, 1972. Free convection heat transfer between vertical parallel plates--one plate isothermally heated and the other thermally insulated. Heat Transfer Japanese Research 1:30-38.

Miyatake, O., T. Fujii, M. Fujii, and H. Tanaka, 1973. Natural convection heat transfer between vertical parallel plates--one plate with a uniform heat flux and the other thermally insulated. Heat Transfer Japanese Research 2:25-33.

Nansteel, M.W., and R. Greif, 1981. Natural convection in undivided and partially divided rectangular enclosures. J. Heat Transfer 103:623-629.

Nansteel, M.W., and R. Greif, 1984. An investigation of natural convection in enclosures with two- and three-dimensional partitions. Int. J. Heat Mass Transfer 27:561-571.

Newell, M.E. and F.W. Schmidt, 1970. J. Heat Transfer 92:159.

Ormiston, S.J., G.D. Raithby, and K.G.T. Hollands, 1985. Numerical Predictions of Natural Convection in a Trombe Wall System. ASME paper #85-HT-36.

Ostrach, S., 1952. Laminar Natural Convection Flow and Heat Transfer of Fluids with and without Heat Sources in Channels with Constant Wall Temperature. NACA TN2863.

Ostrach, S., 1982. Natural convection heat transfer in cavities and cells. 7th Int. Heat Transfer Conf., Munich.

Ostrach, S., and C. Raghavan, 1979. Effect of stabilizing thermal gradients on natural convection in rectangular enclosures. J. Heat Transfer 101:238-243.

Ozoe, H., A. Mouri, M. Hiramitsu, S.W. Churchill, and N. Lior, 1984. Numerical calculation of three-dimensional turbulent natural convection in a cubical enclosure using a two equation model. In Fundamentals of Natural Convection/Electronic Equipment Cooling, L.C. Wilte and L.S. Saxena, eds., ASME HTD 32:25-32.

Poulikakos, D., and A. Bejan, 1983a. Fluid dynamics of an attic space. J. Fluid Mech. 131:251-269.

Poulikakos, D., and A. Bejan, 1983b. Natural convection experiments in a triangular enclosure. J. Heat Transfer 105:652-655.

Schinkel, W.M.M., and C.J. Hoogendoorn, 1983. Natural convection in collector cavities with an isoflux absorber plate. J. of Solar Energy Eng. 105:19-22.

Scott, D., R. Anderson, and R. Figliola, 1985. Blockage of Natural Convection Boundary Layer Flow in a Multizone Enclosure. SERI/TP-252-2847, Golden, CO: SERI.

Shaw, B.H., 1971. Heat and mass transfer by natural convection and combined natural convection and forced air flow through large rectangular openings in a vertical partition. Int. Mech. Eng. Conf. on Heat and Mass Transfer by Combined Forced and Natural Convection. Manchester, England.

Shiralkar, G.S., and C.L. Tien, 1982. A numerical study of the effect of a vertical temperature difference imposed on a horizontal enclosure. Numerical Heat Transfer 5:185-197.

Shakerin, S., M.S. Bohn, and R.L. Loehrke, 1986. Natural convection in an enclosure with discrete roughness elements on a vertical heated wall. 8th Int. Heat Transfer Conf., San Francisco, CA.

Sparrow, E.M., and L.F.A. Azevedo, 1985. Vertical channel natural convection spanning between the fully developed limit and the single-plate boundary-layer limit. Int. J. Heat Mass Transfer 28:1847-1857.

Sparrow, E.M., G.M. Chrysler, and L.F.A. Azevedo, 1984. Observed flow reversals and measured-predicted Nusselt numbers for natural convection in a one-sided heated vertical channel. J. Heat Transfer 106:325-332.

Sparrow, E.M., and C. Prakash, 1981. Interaction between internal natural convection in an enclosure and an external natural convection boundary-layer flow. Int. J. Heat Mass Transfer 24:895-907.

Sparrow, E.M., S. Shah, and C. Prakash, 1980. Natural convection in a vertical channel: I. Interacting convection and radiation. II. The vertical plate with and without shrouding. Numerical Heat Transfer 3:297-314.

Tasdemiroglu, E., F. Ramos Berjano, and D. Tinaut, 1985. The performance results of Trombe-wall passive systems under Aegean Sea climatic conditions. Solar Energy 30:181-189.

Viskanta, R., and D.W. Lankford, 1981. Coupling of heat transfer between two natural convection systems separated by a vertical wall. Int. J. Heat Mass Transfer 24:1171-1177.

Weber, D.D., and R.J. Kearney, 1980. Natural convective heat transfer through an aperture in passive solar heated buildings. In Proc. of 5th National Passive Conf., ASES: Boulder, CO, pp. 1037-1041.

Passive Solar Journal, 3(1), 77-97 (1986)

Solar Load Ratio Design Tool Predictions Compared to Level B Monitoring Data

John Duffy
J. J. Duffy and Assoc.
Winchester, MA 01890
and
University of Lowell
Lowell, MA 01854

David Odegard
J. J. Duffy and Assoc.
Winchester, MA 01890
and
Wisconsin Division of
State Facilities Management
Madison, Wisconsin 53707

Abstract

We generated solar load ratio (SLR) design tool auxiliary energy predictions and compared them with estimates obtained from the Level B monitoring program for 54 sites throughout the United States. On the average, over all houses monitored, the difference between the predicted and measured auxiliary energy values was relatively small. For a given house, however, the discrepancy between the predicted and measured auxiliary was relatively large on the average. The root mean square difference is approximately 30% of the mean measured auxiliary. Using historical data from weather records of nearby cities in place of measured weather

Copyright © 1986 by Marcel Dekker, Inc.

data at the actual site introduced little additional discrepancy between the predicted and measured auxiliary energy values. Much of the discrepancy for individual houses appeared to be due to uncertainties in the measured heat loss coefficient values and measured solar radiation, and limitations in the SLR method. Perhaps this study's main lesson for designers is that on the average, over several buildings, SLR predictions will be relatively accurate compared to measurements of auxiliary. However, for a given passive solar building, the predictions can vary significantly from measurements.

INTRODUCTION

A recent survey by the National Association of Homebuilders (NAHB) indicated that of the homebuilders who had constructed passive solar features (10% of the 772 respondents), the majority felt there was a lack of detailed performance data on passive solar homes (Kando, 1983). In the same survey, 45% of those homebuilders who had not constructed passive solar features (90% of all respondents) gave the following as the third most common reason for their omission of passive solar features: "Don't know how much energy will be saved."

The homebuilders' needs are addressed by the US Department of Energy's Level B Passive Solar Monitoring Program, which has as its objective the determination of the thermal performance of existing passive solar homes. Many of the results of this monitoring project have been published (Swisher and Cowing, 1983; Swisher et al., 1984; Mahajan et al., 1983; McKinstry et al., 1983; Duffy, 1983; Gustashaw, 1983; Holtz et al., 1985). We compared the Level B performance data with predictions based on the solar load ratio (SLR) method in a continuing effort to develop reliable prediction of thermal performance. This paper discusses the methods used and the results of the comparison using 69 site-years of monitoring data. Detailed descriptions of the SLR method are given in Balcomb et al. (1980 and 1984) and in Shurcliff (1983). [Balcomb et al. (1984) is an updated version of Jones et al. (1982).]

A review of the literature reveals that other studies have dealt with design tool comparison with Level B monitoring data. Mahajan et al.

(1983) compared CALPAS and DOE 2 predictions with the California Level B sites. Shea et al. (1983) compared SLR method predictions with California Level B site data. McKinstry et al. (1983) and Tsongas et al. (1983) summarized the comparison of SLR predictions to Level B data from sites in the Northwest (not included in this study). Cowing and Kreider (1983) compared the monitoring data from several Level B sites with the predictions of a design tool they adapted from a method of Gordon and Zarmi (1981).

METHODS

The Level B thermal performance monitoring data used in this study were collected during the 1981-82 and 1982-83 heating seasons. Frey, McKinstry, and Swisher (1982) describe the data collection methods. Mahajan et al. (1983) describe the methods used to collect the data for the houses in California. We used monthly totals of auxiliary energy delivered to the heated zone, internal gains, total heat loss, average interior dry-bulb temperature, average ambient dry-bulb temperature, total horizontal insolation, total insolation on the plane of the dominant passive system glazing, and total hours of monitoring. We used other information about each site as input to the SLR method: latitude, and for each passive system (including east and west glazing if significant) projected vertical and actual aperture area, glazing U value, night insulation U value, overhang geometry, slope, azimuth, and system type designation (Balcomb et al., 1984). We obtained values for these inputs from Swisher and Cowing (1983), Mahajan et al. (1983), Gustashaw (1983), SERI (1982), personal communication with D. Witt and D. Gustashaw, and site handbook information on file at SERI. We obtained much of the passive subsystem glazing area and overhang geometry information from available elevation and section drawings.

The comparison method has all the assumptions inherent in the SLR approach (Jones et al., 1982). Most notable is the assumption that the building acts as a single thermal zone or, for multiple system buildings, that multiple single zones act independently. The notable deviation from this assumption in the SLR approach is the building with a sunspace. Here the building is assumed to have two zones: the main building, which is heated to a "normal" temperature of 65°F, and the sunspace, which is heated to 45°F.

The following three different sets of heating degree days are calculated, and three corresponding SLR predictions are computed:

> Case 1: The degree-days used are computed by summing the measured indoor/outdoor temperature difference over the number of days of monitoring. In this manner the SLR method predicts the total heat needed by the building: auxiliary heat plus internal heat (people, lights, etc.). This total heat is the basis of comparison for case 1. This approach minimizes dependence of the predictions on the heat loss coefficient, which is used in the estimation of the balance point temperature. The balance point temperature is defined as the interior temperature minus the ratio of internal gains energy and the building total heat loss coefficient UA.
>
> Case 2: The degree days are computed using the balance point temperatures (based on measured interior temperatures and measured internal gains) and the measured outdoor temperatures. The SLR predictions then correspond to the measured auxiliary energy (as opposed to the auxiliary plus internal gains energy for case 1). This approach corresponds more closely to the recommended SLR method (Balcomb et al., 1984). It does differ in one important respect: the SLR method is based on the interior thermostat set point temperature rather than the actual interior temperature that is being used in this study. We felt that to estimate the thermostat set point (which in many of the houses in the study varies as a function of time and room in the house) would introduce more error into the study than to use the average of several directly measured interior temperature readings at various locations in the house. One would expect the SLR predictions to be slightly higher than otherwise if the set points were known and used in the method.
>
> Case 3: Case 3 is similar to case 1 except that we used long-term average historical ambient temperatures and insolation data in place of the monitored weather data at the site. The degree days are based on measured interior temperatures and monthly average outdoor temperatures from weather records (as listed in Balcomb et al., 1984). We then compared the resulting SLR auxiliary energy predictions to the measured auxiliary plus internal gains energy. We also used monthly average horizontal

> radiation from weather records in this case. We include this case to estimate what differences in predictions arise from using long-term historical weather data as opposed to using measured weather variables from specific monitoring periods.

The comparison between measured and SLR-predicted auxiliary energy use is based on results for the six months between November 1 and April 30 inclusive. Results are normalized to energy per day and are weighted by the number of days of measured data for each month in obtaining seasonal averages.

The SLR-predicted auxiliary is calculated for the closest reference design. We chose the reference designs primarily on the basis of the thermal mass capacitance to glazing ratios, rather than mass thickness or mass area to glazing area ratios. The method does account for off-reference night insulation as given in the SLR method (Balcomb et al., 1984). The sensitivity corrections for off-reference parameters are carried out in three different ways, as described below. In each of the three ways, the following sensitivity factors are taken into account through the appropriate curves in Balcomb et al. (1984): thermal mass thickness, minimum room temperature, and night setback temperature for direct gain and mass wall systems. For sunspace systems, storage volume ratio, mass thickness, and glazing tilt are taken into account. The solar saving fraction (SSF) sensitivity curves are used in three ways:

> Correction 1: For each of the factors given above, the most appropriate sensitivity curve is used in terms of the city with most similar weather, closest load collector ratio (LCR), closest area of mass to area of glazing, etc. From this curve is found the SSF corresponding to the reference system in question for the value of the parameter in question (e.g., minimum room temperature) and then the SSF corresponding to the actual value of the parameter (along the line of constant LCR or other variable in the graph). The ratio of the latter SSF to the former SSF is formed for each parameter. The ratios are then multiplied together to obtain a final sensitivity correction factor.

> Correction 2: The two SSF values are found in the same manner as above; but instead of forming the ratio of the two SSF values, the difference between the corrected SSF and the reference SSF

> is formed. The sum of these differences is then formed to obtain a final correction for the predicted SSF based on the reference system correlations. This method appears more appropriate than correction 1 for use with predicted SSF values that are negative.
>
> Correction 3: This method corresponds to use of the sensitivity curves suggested by Balcomb et al. (1984). First, the point on the graph is found corresponding to the initial predicted SSF (along the vertical axis) and the reference value of the parameter in question (along the horizontal axis). The curve of constant LCR (or other variable given in the graph) is followed to the point directly above the parameter value of the actual house in question. The corrected SSF is then read off from the vertical axis. The order in which these corrections are made to the SSF values is arbitrary so that the final corrected SSF is not unique for a given set of sensitivity parameters. The order in which the corrections are made in this study is the same as the order in which the sensitivity parameters are listed above.

The building heat loss coefficient UA is a monthly equivalent heat loss coefficient computed by dividing the total heat loss of the Level B data by the measured degree days based on the actual average interior temperature. The UA values used in the actual monitoring process can vary with time according to night insulation position, infiltration rates (from wind and stack effects), air-to-air heat exchangers, etc., depending on the particular house and the installed sensors. The UA computed above has that single value that, if multiplied by the measured degree days, would result in the same total heat loss generated from the monitoring. The SLR parameters NLC (building net load coefficient) and LCR (load collector ratio) are computed as monthly variables by subtracting the collector's ASHRAE-type heat loss from the measured UA. The collector U value is taken from ASHRAE Fundamentals (0.43 Btu/h °F for a wind speed of 3 mph, for double glazing with a 0.5 in. gap, and with a 70°F temperature differential and 0.3 Btu/h °F for triple glazing). For sunspaces the "collector" U value is taken as LCR_S (for the appropriate reference design) times the actual projected area. Since the measured UA values take into account the night insulation in place, the NLC variable is obtained by assuming that the night insulation is in place 14 hours per day (to be consistent with the SLR method assumption).

If a collector plane was not within 5 degrees of a pyranometer, the collector-plane insolation is obtained by transposing measured horizontal insolation to the collector plane and correcting for ground reflectance and transposition correlation error. Such error is corrected by multiplying the transposed insolation by the ratio of insolation measured on the tilted pyranometer to the insolation predicted on the same surface on the basis of the measured horizontal insolation. If this ratio is less than 0.1, it is assumed that the tilted pyranometer was malfunctioning and the horizontal one was working properly; therefore, no correction is applied. This ratio is used as a correction to take into account ground and snow reflectance and shading of the horizontal pyranometer by snow cover.

Shading by fixed overhangs is calculated according to the correlations presented in Balcomb et al. (1980). The dimensions of the overhang may not be explicitly treated by this algorithm: if the overhang ratios are too low, no shading is assumed; or if the ratio of horizontal overhang to the glass height is greater than 0.5 (the limit of the algorithm), then it is assumed to equal 0.5.

The absorbed insolation is based on transmission and absorption factors for double glazing (only a couple of the sites had a majority of the south aperture in triple glazing) as presented in Balcomb et al. (1984). Absorptances for sunspaces are based on the combined transposition, transmission, and absorption factors provided in Jones et al. (1982) for the reference designs.

A more detailed explanation of the comparison method and the computer program that carries out the calculations involved in this method is available from the authors.

RESULTS

Table 1 summarizes the results of applying this method to 69 site-years of Level B monitoring data. The average daily values of predicted and measured auxiliary for the corresponding cases and sensitivity corrections described in the previous section are given for the heating season. Recall that auxiliary for cases 1 and 3 is the sum of the auxiliary heat delivered to the living zone and the internal gains, while the auxiliary for case 2 is the auxiliary heat

Table 1. Comparison of Measured and Predicted Values

Site, Year Code	Main System Type Code	Measured Auxiliary Case 1,3	Measured Aux. Case 2	Pred. Aux. Case 1 No Corr.	Pred. Aux. Case 1 Corr. 2	Pred. Aux. Case 2 No Corr.	Pred. Aux. Case 2 Corr. 1	Pred. Aux. Case 2 Corr. 2	Pred. Aux. Case 2 Corr. 3	Pred. Aux. Case 3 No Corr.	Pred. Aux. Case 3 Corr. 2	Absorbed Solar Energy	Useful Solar Energy
WA1	DG B1	81967	22412	30513	26154	11532	8306	8392	8563	20832	16635	430787	130817
WD1	DG B1	107292	17899	91602	80762	19243	14387	14340	18998	58157	49175	123580	55954
WE1	DG A1	94558	22887	114260	72648	47019	18812	25101	33275	76818	44580	65205	57183
WF1	SS B1	122514	72117	71195	95071	43779	53752	62473	52344	70450	92000	201972	110616
WG1	DG A1	136976	58721	234013	173804	163984	142585	116155	124873	174195	122497	260762	243512
WH1	DG A1	152422	30630	222236	199364	103742	101905	90122	57887	111322	94540	114106	149958
WI1	TW A3	57861	2178	28554	42641	6789	17144	15162	12673	15452	28686	226628	79818
WJ1	DG C1	137947	88434	138207	233803	89462	117919	160252	141816	127903	223432	80140	53266
WK1	DG A1	93272	47246	94071	82712	50896	49064	43653	50040	78987	67418	56833	34873
WL1	DG B1	130558	61937	122316	164715	54269	65805	76003	79033	118511	161113	26324	7782
WM1	DG A1	56431	2015	86076	59270	12048	0	0	0	62612	41348	281397	162109
SA1	DG C3	458280	333523	541879	555548	424810	408638	435854	384577	296072	309025	96552	184149
SF2	DG C1	294448	245136	306982	304859	258056	258188	256241	267133	231881	230045	50346	47154
SG2	SS C1	401356	270541	462964	533812	336897	175226	389465	343840	384569	451689	34455	105375
SJ1	SS C2	210374	96853	236648	271957	136328	144435	159239	129991	137108	165289	88398	112940
SJ2	SS C2	233982	129747	248848	289179	158235	172799	187173	149820	175564	211968	135050	134743
SK1	TW A2	128010	66136	158665	189912	101728	108896	123094	121076	117302	141268	43831	67352
SK2	TW A2	149138	80846	178562	214117	115702	123922	140167	137869	129281	155872	47301	69618
SL2	WW B4	128300	62553	31119	31119	8253	24934	8253	16207	37201	37201	122650	41426
SM1	DG B1	211546	64880	255724	217110	111687	98727	91634	106242	222699	183460	75950	91105
SN1	WW A1	118887	67704	75068	71006	45781	43925	42721	29378	49775	46209	123101	88543
SN2	WW A1	125209	77674	72992	68718	46570	44225	43267	29065	73319	68765	141002	84203
MB1	DG A3	172280	71436	235259	233572	137623	141073	136548	136701	227331	225701	61013	105719
MC1	DG A3	247545	188252	214772	254545	158264	191994	190955	184609	197623	233748	227789	86847
MD2	TW I4	146430	76667	68518	62652	10559	7356	7068	4800	73536	67527	150536	26402
ME2	DG A1	118552	15114	161144	143800	61510	78055	52891	65820	158543	141327	74930	57981
MI2	SS C1	241444	137611	285476	328383	191481	197646	223395	202119	301810	346901	127156	164194
MM1	SS B1	304140	158862	208471	204868	105157	104533	102824	107335	185733	182294	241408	108057
MN2	DG A1	129610	87351	138852	132616	99715	108787	94811	75195	151987	145042	89945	68078
MP2	DG C1	222716	138421	180079	122503	97726	0	59267	65462	209433	145515	110407	34116
BA1	DG B3	146297	107604	245066	183714	209722	184113	154126	145168	259188	194029	262426	265032
BA2	DG B3	147846	97980	166059	123721	122128	102712	86614	80893	123263	83643	219323	160761
BB1	DG A3	196149	185874	246254	244204	236289	236284	234312	239749	213654	211936	68153	96754
BD1	DG B3	139168	49024	170677	161335	83846	89358	78153	80644	153944	145392	90763	91539
BD2	DG B3	137258	77916	245448	233583	188193	187115	178744	190949	282211	268500	64745	155204
DA1	DG B1	144075	36295	170228	162089	87532	87503	81911	72274	184286	175201	264978	204862
DC1	DG B3	127697	99031	204451	181734	177536	164156	156775	130424	249300	224871	195038	204393
DD1	DG B3	203163	128635	257076	229002	191158	171340	167178	190130	257806	229252	379409	305125
DD2	DG B3	260090	153773	160303	154942	84481	83410	80606	83318	130542	125289	330837	123961
DE1	DG C1	275308	182908	302321	262150	215888	190799	182057	202286	306111	264698	432794	311212
DF1	DG C3	198238	117207	170184	147812	85941	78255	69645	89239	180636	156084	221148	130500
DF2	DG C3	240732	150529	166582	160728	95890	93037	91477	82249	151974	145950	230568	92540
DG1	DG B3	219086	134432	277970	346022	200171	233730	254684	276894	270068	342779	206158	206809
DH1	SS B1	82088	39604	62807	68758	31461	35006	36026	34410	81574	87718	144430	100671
DH2	SS B1	80171	37327	13969	18398	3234	5196	4839	3209	38667	42963	192084	49108
DI1	DG B1	259311	138530	198559	214118	95679	105259	106090	132199	206892	222964	256235	105125
DJ1	DG B1	120237	68281	149036	86682	102847	77368	54366	50443	144597	81586	141705	113780
DK1	TW A4	140670	70685	76290	73453	39902	39762	37719	40023	74691	71843	369202	163351
DL1	DG A1	168947	110348	231716	202850	177234	171069	153342	158555	245501	215529	183468	170399
DM2	SS B2	115822	31601	854	4514	129	2299	2709	3655	209	2996	446581	133344
DN2	DG A1	138153	70893	166966	166966	100425	100093	100425	103567	125688	125688	37115	51715
DT2	DG A1	149046	0	163845	219563	22104	43201	36000	37347	165937	223342	57254	49592
NA1	DG C3	322131	158927	264863	275952	131082	133019	136912	124919	217923	227505	187054	96260
NA2	DG C3	277174	205080	262367	273045	196625	199548	205381	187619	265615	276526	168803	125707
NB1	SS B2	122119	85751	96775	93581	73268	72395	70601	75192	67956	65410	104233	97873
NC1	SS C2	251815	161546	288625	298808	204933	208624	212646	207137	232266	241131	84211	120389
NC2	SS C2	193123	105320	162180	175695	86243	90248	94847	87591	130934	143440	81793	50072
ND1	DG A1	185643	154446	196582	196196	165898	164236	165564	200481	186199	185851	58510	47757
ND2	DG A1	156948	125420	174086	173745	143059	141832	142771	172707	184590	184247	48025	47480
NH1	SS A3	147753	105973	135734	142886	105069	131691	111042	130318	137206	143811	146350	106432
NH2	SS A3	115920	85519	106845	112249	84743	101880	89341	106582	127286	133169	112373	88622
NI2	DG A1	245231	184654	229504	155611	174136	173355	114692	143365	190106	130202	110076	67635
NJ2	SS C3	138332	68599	67154	67899	18109	11054	18529	17639	24869	25624	70972	21661
NK1	DG B1	193618	101519	190493	135470	99920	44116	65300	89534	183517	133825	94160	55034

Table 1. Comparison of Measured and Predicted Values

(concluded)

Site, Year Code	Main System Type Code	Measured Auxiliary Case 1,3	Measured Aux. Case 2	Pred. Aux. Case 1 No Corr.	Pred. Aux. Case 1 Corr. 2	Pred. Aux. Case 2 No Corr.	Pred. Aux. Case 2 Corr. 1	Pred. Aux. Case 2 Corr. 2	Pred. Aux. Case 2 Corr. 3	Pred. Aux. Case 3 No Corr.	Pred. Aux. Case 3 Corr. 2	Absorbed Solar Energy	Useful Solar Energy
NK2	DG B1	188177	107303	182912	129973	103425	57362	68345	91933	193022	141949	94293	52932
NL1	DG A1	93878	87815	98723	21653	93744	61526	19456	23583	84813	19171	106284	75852
NL2	DG A1	139874	133185	138092	169981	132222	129901	163034	160756	132501	164921	67775	55253
NM1	SS A1	135825	105498	124429	124266	106513	106593	106365	106365	161353	161184	283941	182687
NM2	SS A1	152229	87845	119840	119696	76583	76650	76472	83484	175582	175421	197647	134526

Note: All numerical values are in Btu/day.

delivered to the living zone without the internal gains. Also listed in Table 1 are the absorbed solar energy (incident radiation times the transmittance and absorptance) and "useful" passive solar estimated from the monitoring data on a daily average basis. The "useful" passive solar energy derived from the Level B data is obtained by subtracting from the total heat loss for the building the sum of the measured auxiliary and internal gains energy. Also listed for each site are the code values for the dominant passive system reference type. The codes are those designated in Balcomb et al. (1984). The site-year codes have as the first character the letter corresponding to the region of the country or the manufactured buildings program: W for California, S for the South, M for Mid-America, B for the manufactured buildings program (the first site is in Denver, and the other two are in the Midwest), D for the Denver area, and N for New England. The second character is a letter designating the site within the region, while the last character represents the last number of the year of the start of the heating season in which the data were collected. Fifty-four different sites are represented. Table 2 lists the predicted solar savings fractions (SSF) for each site and year. Detailed listings of monthly input data and SLR output data are available from the authors.

Figure 1 plots the predicted and measured auxiliary energy values for case 1 with no corrections. We performed several tests to compare the predicted and measured auxiliary energy values for all the cases in several combinations with corrections. We computed the mean of the difference between the measured and predicted

Table 2. Predicted Solar Saving Fractions

Site, Year Code	System Type	SSF Case 1	SSF Case 2	SSF SSF Case 3	Ratio Case 2 Corr. 3	Abs Solar Useful Sol
WA1	DG B1	0.23	0.60	0.45	0.7	3.29
WD1	DG B1	0.32	0.69	0.48	0.69	2.21
WE1	DG A1	0.17	0.35	0.28	0.54	1.14
WF1	SS B1	0.18	0.36	0.10	0.23	1.83
WG1	DG A1	0.21	0.30	0.32	0.47	1.07
WH1	DG A1	-0.17	0.09	0.20	0.49	-0.76
WI1	TW A3	0.63	0.85	0.78	-0.72	2.84
WJ1	DG C1	0.13	0.24	0.20	-0.2	1.50
WK1	DG A1	0.09	0.23	0.25	0.24	1.63
WL1	DG B1	0.05	0.18	0.08	-0.2	3.38
WM1	DG A1	0.42	0.87	0.47	1	1.74
SA1	DG C3	-0.11	-0.08	0.35	0.025	0.52
SF2	DG C1	-0.01	0.01	0.12	-0.03	1.07
SG2	SS C1	-0.04	-0.02	0.09	-0.04	0.33
SJ1	SS C2	0.06	0.16	0.31	0.2	0.78
SJ2	SS C2	0.13	0.23	0.32	0.27	1.00
SK1	TW A2	0.09	0.14	0.12	-0.02	0.65
SK2	TW A2	0.09	0.14	0.12	-0.02	0.68
SL2	WW B4	0.24	0.67	0.12	0.35	2.96
SM1	DG B1	0.00	0.16	0.14	0.2	0.83
SN1	WW A1	0.08	0.25	0.30	0.52	1.39
SN2	WW A1	0.15	0.30	0.20	0.56	1.67
MB1	DG A3	0.02	0.10	0.02	0.11	0.58
MC1	DG A3	0.08	0.18	0.07	0.04	2.62
MD2	DG A1	-0.87	0.52	-0.96	0.78	5.70
ME2	DG A1	-0.02	0.22	-0.01	0.16	1.29
MI2	SS C1	0.00	0.10	0.00	0.05	0.77
MM1	SS B1	0.13	0.32	0.19	0.31	2.23
MN2	DG A1	-0.34	-0.22	-0.31	0.08	1.32
MP2	DG C1	-0.03	0.16	-0.08	0.44	3.24
BA1	DG B3	0.28	0.32	0.28	0.53	0.99
BA2	DG B3	0.29	0.38	0.44	0.59	1.36
BB1	DG A3	0.04	0.04	0.01	0.03	0.70
BD1	DG B3	0.12	0.29	0.14	0.32	0.99
BD2	DG B3	0.01	0.04	0.01	0.03	0.42
DA1	DG B1	0.27	0.46	0.29	0.55	1.29
DC1	DG B3	0.30	0.33	0.20	0.51	0.95
DD1	DG B3	0.36	0.44	0.37	0.445	1.25
DD2	DG B3	0.40	0.56	0.50	0.57	2.67
DE1	DG C1	0.27	0.38	0.28	0.42	1.39
DF1	DG C3	0.36	0.56	0.38	0.54	1.69
DF2	DG C3	0.37	0.52	0.45	0.59	2.49
DG1	DG B3	0.23	0.31	0.30	0.04	1.00
DH1	SS B1	0.31	0.55	0.14	0.51	1.43
DH2	SS B1	0.80	0.87	0.42	0.87	3.91
DI1	DG B1	0.20	0.42	0.19	0.2	2.44
DJ1	DG B1	0.17	0.27	0.21	0.64	1.25
DK1	TW A4	0.52	0.67	0.53	0.67	2.26

Table 2. Predicted Solar Saving Fractions (Continued)

Site, Year Code	System Type	SSF Case 1	SSF Case 2	SSF Case 3	SSF Case 2 Corr. 3	Ratio Abs Solar Useful Sol
DL1	DG A1	0.12	0.18	0.10	0.27	1.08
DM2	SS B2	0.97	0.99	0.99	0.83	3.35
DN2	DG A1	0.08	0.14	0.14	0.11	0.72
DT2	DG A1	0.06	0.49	0.08	0.14	1.15
NA1	DG C3	0.16	0.21	0.20	0.25	1.94
NA2	DG C3	0.14	0.21	0.15	0.25	1.34
NB1	SS B2	0.08	0.16	0.19	0.14	1.06
NC1	SS C2	0.01	0.07	0.08	0.06	0.70
NC2	SS C2	0.00	0.17	0.13	0.155	1.63
ND1	DG A1	-0.02	0.01	-0.07	-0.2	1.23
ND2	DG A1	-0.02	0.01	-0.08	-0.2	1.01
NH1	SS A3	0.17	0.23	0.09	0.04	1.38
NH2	SS A3	0.13	0.19	0.05	-0.02	1.27
NI2	DG A1	-0.06	0.00	-0.08	0.18	1.63
NJ2	SS C3	-1.25	-0.08	0.18	-0.05	3.28
NK1	DG B1	0.00	0.16	-0.07	0.25	1.71
NK2	DG B1	0.00	0.15	-0.10	0.24	1.78
NL1	DG A1	0.19	0.21	0.19	0.8	1.40
NL2	DG A1	0.00	0.01	0.06	-0.2	1.23
NM1	SS A1	0.24	0.28	0.05	0.28	1.55
NM2	SS A1	0.17	0.31	-0.09	0.25	1.47

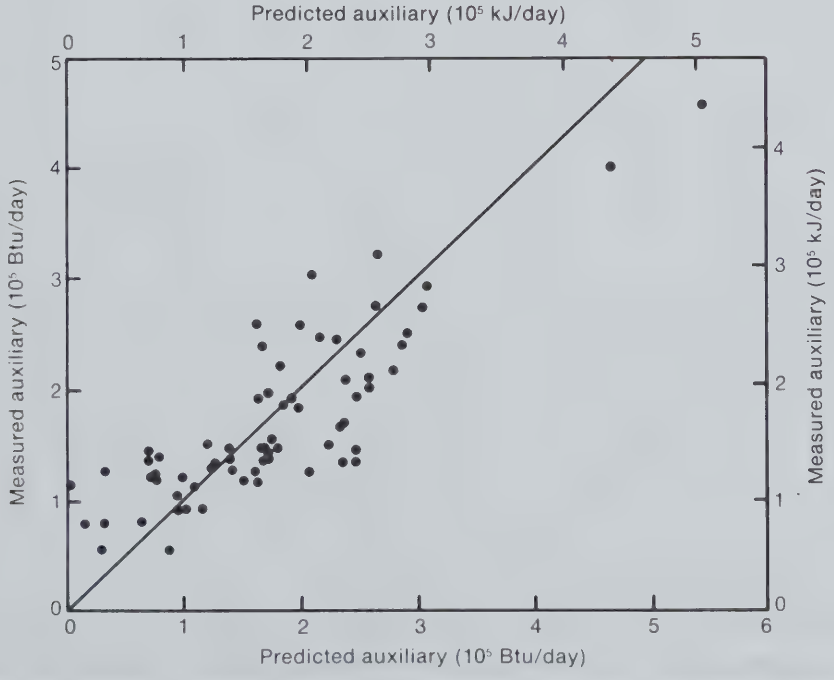


Figure 1. Measured compared to predicted auxiliary energy (case 1, no corrections)

values (i.e., the measured minus predicted) across all the site-year samples to make apparent any consistent bias in over- or underprediction. In addition, we computed the standard deviation of the difference to obtain a measure of the average dispersion of the differences about the mean difference. The root mean square difference was computed to obtain an average dispersion for a given house. A linear regression of measured auxiliary versus predicted auxiliary was performed. A perfect correspondence between measured and predicted auxiliary would have resulted in a correlation coefficient r of 1.0, a slope of 1.0, and an intercept of 0. Table 3 summarizes the results of these tests. The mean difference, standard deviation of the difference, the root mean square difference, and the intercept of the regression line with the vertical axis (measured auxiliary) were all computed in Btu per day and then expressed in percent of the average measured auxiliary energy in order to make comparisons easier.

On the average, the predicted auxiliary is higher than the measured auxiliary for case 2 probably because the measured interior temperatures were higher than the set points and because of the conservative nature of the SLR method. For case 2 with no corrections, the bias is significant at the 5% confidence level based on a paired-t test. For case 1 the difference is essentially zero. For case 2 with the third type of sensitivity correction (i.e., the method most closely corresponding to that recommended by Balcomb et al., 1984), the average difference was just under 10% of the average of the measured auxiliary energy values. The spread of the differences about these relatively small means is very large as evidenced by the values of the standard deviations ranging from 30% to 48% of the mean measured auxiliary. Thus, on the average, the correspondence between the predicted and auxiliary is good, particularly since the uncertainty in the auxiliary and internal gain measurements are estimated at between 5% and 10% (standard deviation relative to the mean), depending on the type of auxiliary heating system used (Duffy, 1983). There is a tendency toward underprediction for houses with low auxiliary use and overprediction for residences with high auxiliary use, as exhibited by positive intercept and slope less than unity for all cases and corrections. However, deviation is considerable between the predicted and measured auxiliary values for a given house. It is also evident from Table 3 that the various sensitivity corrections resulted in less close correspondence between

Table 3. Test Results of Comparison of Measured and Predicted Auxiliary Energy

Case No.	Cor. No.	Aver. Diff. (M - P)	S.D. of Diff.	R.M.S. Diff.	Intercept	r	Slope	Aver. Meas. Aux. (Btu/day)	Sample Size
		(% of Mean Measured Aux.)							
1	0	-0.15	29.52	28.22	32.72	0.84	0.67	173382	69
1	2	1.58	33.76	33.55	40.32	0.83	0.61	173382	69
2	0	-11.62	42.54	43.80	24.85	0.84	0.67	100705	69
2	1	-6.62	47.08	47.21	30.26	0.78	0.65	100705	69
2	2	-8.88	47.44	47.87	32.45	0.83	0.62	100705	69
2	3	-8.99	44.11	44.70	28.40	0.83	0.66	100705	69
3	0	9.57	33.57	34.68	38.69	0.73	0.68	173382	69
3	2	11.18	35.23	36.71	44.19	0.73	0.63	173382	69
(The following are for case 1, no correction.)									
Subsample Type									
Direct Gain		-8.57	26.09	27.18	17.18	0.82	0.76	179997	44
Sunspace		11.68	27.30	28.95	40.22	0.93	0.68	179353	17
Low Mass DG		-17.60	22.11	27.78	12.18	0.80	0.75	148639	18
Med. Mass DG		-10.68	33.67	34.37	50.27	0.56	0.45	165728	17
High Mass DG		3.85	17.84	17.25	33.72	0.95	0.69	269663	9
California		-5.23	43.70	41.99	60.41	0.77	0.38	106527	11
South		-4.47	23.92	23.24	25.60	0.97	0.71	223594	11
Mid-America		-4.85	33.94	32.73	53.17	0.45	0.45	186845	11
Denver		1.02	37.24	36.26	53.78	0.65	0.47	169315	19
Northeast		7.21	14.43	15.74	18.73	0.92	0.88	179988	17

the measured and predicted auxiliary values for the sample of houses as a whole. Using historical weather data in place of measured outside temperatures and solar radiation in case 3 resulted in an increase in bias toward underprediction (significant at the 5% level) but a negligible increase in the spread, or standard deviation, of the differences, relative to case 1. This phenomenon is undoubtedly because of the year-to-year variations in weather.

To determine some possible causes of the discrepancy between individual measured and predicted auxiliary energy values, we divided the data into subsamples according to several categories for case 1 with no correction: dominant passive system type, relative amount of thermal mass for direct gain systems, and geographic region. Table 3 summarizes the statistics for the tests of comparison.

The difference is minor in the root mean square differences for the direct gain and sunspace system types. However, the direct gain bias is significantly different from zero and from the bias for sunspaces. There were too few Trombe wall and water wall systems to evaluate meaningfully.

A systematic pattern of bias is apparent as a function of thermal mass levels for direct gain houses with low mass systems exhibiting overprediction (significant at the 5% level) and high mass systems showing underprediction. The difference between the bias for low mass and the bias for high mass was statistically significant. However, no clear pattern emerges in the average dispersion of the difference between the measured and predicted auxiliary being dependent on relative mass levels in direct gain houses. The sample of sunspace systems was not large enough to break down into mass groupings for meaningful comparison tests.

Table 3 also shows the results of grouping the sites by geographical region. The bias for each region was not significantly different from zero or from the bias for any other region. The Northeast sites did have a significantly better correspondence between the measured and predicted auxiliary as indicated by the standard deviation of the differences compared to every other region in F-tests. The sites in the South appear to have good correspondence on the basis of the regression statistics because of the close correspondence of two sites with very high measured auxiliary use. The houses in the South with lower auxiliary use have no better correspondence than the houses in other parts of the country. In general, no clear pattern emerges of correspondence between the measured and predicted auxiliary energy being highly dependent on geographic region.

One possible source of the individual discrepancies between the predicted and measured auxiliary values may lie in the uncertainties in measuring the total heat loss coefficients of the houses. The conduction component of the total UA is determined with a coheating test, while the infiltration component is estimated through a model taking into account the stack effect and wind speed with parameters determined by blower door testing. Frey, McKinstry, and Swisher (1982) give the methods and Duffy (1983) discusses the sources of uncertainty. To test for a possible relationship between the UA and the difference in auxiliary predictions (for case 1, no correction) and measurements, we performed a regression of this difference in auxiliary estimates versus the difference between the absorbed solar and useful passive solar energy values. Figure 2 shows a scatter plot. The correlation coefficient was 0.75 (statistically significant at the 5% error level), the slope was -0.49, and the intercept was 23689 Btu/day. A very clear relationship is evident. The useful passive solar energy is highly dependent on the UA because it is estimated by taking the difference between the total heat loss from the house (UA times the degree days) and the sum of the delivered auxiliary energy and internal gains. The absorbed solar energy is dependent on the pyranometer readings and not on the UA. Similarly, the measured auxiliary is independent of the UA value. Exceptions to this independence of UA and measured auxiliary are those houses with furnace systems whose efficiencies were estimated through a coheating test, which is also used to estimate the heat loss coefficient. Nevertheless, this dependence for those houses is very indirect and probably minor compared to the actual auxiliary delivered to the living zone [the uncertainty was estimated at roughly 10%, standard deviation relative to the mean auxiliary, by Duffy (1983)]. However, the predicted auxiliary is highly dependent on the gross UA and the building net load coefficient (NLC). Thus, if the measured UA is higher than the real value, the absorbed solar minus the useful passive energy will go down, while the predicted minus measured auxiliary will go up. Figure 2 exhibits exactly that kind of relationship. Thus, much of the discrepancy between the predicted and measured auxiliary values is probably because of discrepancies between the measured and actual heat loss coefficient values. Also, measurement uncertainties in solar insolation possibly could account for the pattern in Figure 2, but those uncertainties are considered minor compared to those associated with the UA estimates.

Shea et al. (1983) found with the California Level B sites that higher discrepancies between the SLR predictions and the auxiliary measurements increased for those houses with widely varying interior temperatures. The SLR method is based on the assumption that interior temperatures are controlled in a fixed range, although

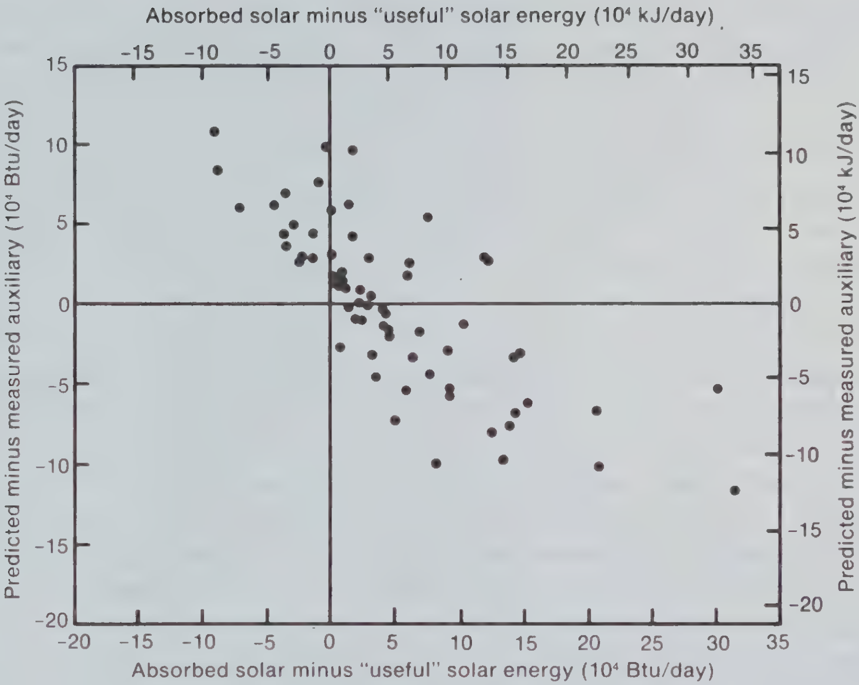


Figure 2. Measured minus predicted auxiliary energy (case 1, no correction) compared to absorbed solar minus useful solar energy

sensitivity curves are available for compensating for night setbacks and other temperature fluctuations. Shea et al. (1983) also found that use of the SLR method sensitivity curves decreased the discrepancy between the predictions and measurements. A similar finding was not obtained with the California sites in this study. However, the results of this analysis are in general consistent with the other design tool comparison studies cited earlier in the report except that Cowing and Kreider (1983) got much less scatter in comparing their design tool predictions with Level B data from 11 of the sites in this study. The overall comparison results in this study are not substantially different from the SLR predictions compared to Level C data (i.e., energy-audit-type estimates) for 86 sites in the Northeast (Duffy and Odegard, 1982).

Comparison of the absorbed solar and useful passive energy values is useful because the absorbed solar is an independent measure of the solar input whereas the useful passive solar is arrived at by independent measurements (of other than radiation). One would not expect them to be equal, however, since the useful passive solar energy does not include (or at least should not include) any absorbed solar energy that was vented or dumped (particularly in the swing seasons of fall and spring). One would expect the total absorbed solar to be higher than the useful solar quantity. One would expect a close relationship between the two variables, however. Tables 1 and 2 indicate that, in fact, the absorbed solar is higher on the average than the useful solar. A regression of absorbed solar versus useful solar resulted in an r of 0.66, a slope of 1.06, and an intercept of 40,568 Btu/day. The root mean square difference between the absorbed solar and useful solar values is 90,865 Btu/day (58% of the mean absorbed solar value and 84% of the mean useful solar value). Some of this discrepancy may be due to venting of collected solar energy, uncertainty in actual internal gains, etc. Much of it is also undoubtedly a result of difficulties in determining actual UA values and other monitoring limitations (Duffy, 1983).

SUMMARY AND CONCLUSIONS

We generated solar load ratio (SLR) design tool auxiliary energy predictions and compared them with estimates obtained from the Level B monitoring program for 54 sites throughout the United States (except the Southwest) with 69 site-years of heating season data. We developed three predictions of auxiliary energy based on (1) measured degree days with respect to actual interior temperatures (to be compared to measured auxiliary plus internal gains energy), (2) degree days with respect to the balance point temperature (to be compared to measured auxiliary not including internal gains), and (3) degree days and horizontal radiation from historical weather records. We adjusted these three predictions for variations in the thermal parameters of the actual houses to those of the reference buildings in the SLR method. We used three correction methods with the sensitivity curves in Balcomb et al. (1984) based on (1) the ratio of the SSF corresponding to the actual parameter located along the line of constant load collector ratio (LCR) to the SSF of the SLR reference building, (2) the difference in the above two SSF values, and (3) the adjusted SSF corresponding to the actual parameter along the line of constant LCR starting from the intersection of the original predicted SSF and the reference parameter. We compared the measured and predicted auxiliary for combinations of the above cases and sensitivity correction methods, and for subsamples grouped according to dominant passive system type, relative thermal mass levels for direct gain systems, and geographic regions. In addition, an indirect measure of heat loss coefficient accuracy (absorbed solar minus "useful" solar energy from the Level B monitoring estimates) was related to the difference between measured and predicted auxiliary energy values. Based on these computations and analyses, we made the following conclusions and observations.

On the average, for all houses monitored, the difference between the predicted and measured auxiliary energy values is relatively small (ranging from almost zero to about 11% of the mean measured auxiliary, depending on the prediction method). For a given house, however, the discrepancy between the predicted and measured auxiliary is relatively large on the average. The root mean square difference is approximately 44% of the mean measured auxiliary for the prediction method most closely corresponding to that recommended in Balcomb et al. (1984). There is a tendency toward underprediction for houses with relatively small auxiliary energy consumption and overprediction for houses with relatively large auxiliary energy use.

Using historical data from weather records of nearby cities in place of measured weather data at the actual site introduces little additional random discrepancy between the predicted and measured auxiliary energy values, relative to the other uncertainties involved in both the SLR method and the monitoring process.

The corrections to the predicted auxiliary energy values based on the sensitivity curves resulted in more rather than less discrepancy between the measured and predicted auxiliary for the houses as a whole. For some houses, the sensitivity adjustments improved the correspondence between the measured and predicted values.

The random discrepancy between the measured and predicted auxiliary energy values did not seem to be related to the passive system type, the relative level of thermal mass in direct gain systems, or the geographic region. Significant bias was detected for direct gain and low mass, direct gain systems. Much of the discrepancy for individual houses appears to result from uncertainties in the measured heat loss coefficient values used in the monitoring analysis.

Differences in the reference designs of the SLR method and in the actual houses undoubtedly leads to discrepancies also. How the SLR method treats multiple passive system types in one building may introduce additional uncertainties.

Other possible sources of the discrepancy between the measured and predicted auxiliary energy values may be due to simplifications involved in the SLR method itself, which is based on curve fitting to results of more detailed simulation design tool models. There are also uncertainties involved in the Level B monitoring process (Duffy, 1983). The choice of reference system and the application of sensitivity corrections are subjective and therefore introduce some uncertainty into the SLR process.

Another obvious point in this analysis is how internal gains are handled in the SLR method, and the relative size of internal gains with respect to the UA or NLC values can have a tremendous effect on the SSF (see Table 2). It is quite evident that the meaning and value of the SSF is minimal in itself. This finding is consistent with the cautionary remarks in Balcomb et al. (1984).

We have several suggestions for future work in design tool comparison with Level B monitoring data. Use estimated UA instead of measured heat loss coefficients in the above analysis to test for changes in the magnitude of the discrepancy between the SLR predictions and the measured auxiliary energy. Use least-squares parameter estimation methods to extract better UA estimates from existing Level B monitoring data and repeat the above analysis with the revised UA estimates. Analyze the effect of adding or removing east and west glazings from the SLR predictions. Compare the results of high solar aperture houses (relative to floor area) to those of houses with low relative aperture areas. Use other design tools in addition to the SLR method, such as the unutilizability method and simple thermal network models.

Perhaps the main lesson this study offers designers is that, on the average, over several buildings, SLR predictions will be relatively accurate compared to measurements of auxiliary (whether it includes internal gains or not). However, for a given passive solar building, the predictions can vary significantly from measurements.

ACKNOWLEDGMENTS

The assistance of Fouad Younan, Melhem Ash, and Steve Ludwig in tabulating and entering data is gratefully acknowledged. Acknowledgment is due to all those who have participated in the Level B Monitoring Program, especially the homeowners of the monitored houses, and Blair Hamilton, Joel Swisher, Don Frey, Bill Tolbert, Don Witt, Dave Gustashaw, George Yeagle, Jim Boswell, S. Mahajan, Michael Shea, Dan Mort, Charles Newcomb, Mark McKinstry, and Aeolian Kinetics.

REFERENCES

Balcomb, J., C. Barley, R. McFarland, J. Perry, Jr., W. Wray, and S. Noll, 1980. Passive Solar Design Handbook. Vol. 2, DOE/CS-0127/2, Washington, DC: U.S. Department of Energy.

Balcomb, J., R. Jones, R. MacFarland, W. Wray, 1984. Passive Solar Heating Analysis. Atlanta, GA: ASHRAE.

Cowing, T., and J. Kreider, 1983. A new passive solar space heating system design method for the United States. In Proc. of the 8th National Passive Solar Conf., Sept. 7-9, 1983, Santa Fe, NM. Boulder, CO: ASES. pp. 45-88.

Duffy, J., 1983. Estimation of the Uncertainty in Class B Monitoring Results, J.J. Duffy and Assoc. report to SERI.

Duffy, J., and D. Odegard, 1982. Thermal performance and design tool comparison for 86 northeast passive solar residences as estimated from Class C audits. In Proc. of the 1982 AS/ISES Annual Meeting, p. 721.

Frey, D., M. McKinstry, and J. Swisher, 1982. Class B Installation Guide, SERI/TR-254-1671, Golden, CO: SERI.

Gordon, J., and Y. Zarmi. 1981. Analytic model for passively heated solar homes. I Theory. Solar Energy 27:331-342.

Gustashaw, D., 1983. A Comparison of the Analytically Developed and Field Measured Overall Conductive Heat Transfer Coefficients in Passive Solar Residential Construction. EGS, Inc. report to SERI.

Holtz, M., D. Frey, R. Bishop, and J. Swisher, 1985. The future of passive solar design. Solar Age 10(10):49-56.

Jones, R. (ed.), J. Balcomb, C. Kosiewicz, G. Lazarus, R. McFarland, and W. Wray, July 1982. Passive Solar Design Handbook, Vol. 3, DOE/CS-0127/3, Washington, DC: U.S. Department of Energy.

Kando, P., 1983. How builders view passive housing. Solar Age 8(9):15.

Mahajan, S., C. Newcombe, M. Shea, and D. Mort, 1983. Performance of Passive Solar and Energy Conserving Houses in California. SERI/STR-254-2017. Golden, CO: SERI.

McKinstry, M., P. Busse, L. Lambert, and P. Gillen, 1983. Heating season results from the Bonneville Power Administration Class B Passive Solar Monitoring Program. In Proc. of the 8th National Passive Solar Conf. Sept. 7-9, 1983, Santa Fe, NM. Boulder, CO., ASES. pp. 211-227.

SERI. 1982. Solar Design Briefs. Published for the Denver Metro Home-builders Program Solar Tour of Homes. Golden, CO: SERI.

Shea, M., S. Mahajan, C. Newcombe, and D. Mort, 1983. Development of Design Guidelines for Passive Solar Residential Design for CSUS/CEC Data Base. California State University at Sacramento report to Bonneville Power Admin.

Shurcliff, W.A., 1983. Simplifying Guide to the Los Alamos Vol. #3 Passive Solar Design Analysis. Cambridge, MA: Shurcliff.

Swisher, J., N. Carlisle, P. Oatman, and K. Russell, 1984. Passive Solar Performance, Summary of 1982-1983 Class B Results. SERI/SP-271-2362, Golden, CO: SERI.

Swisher, J., and T. Cowing, 1983. Passive Solar Performance, Summary of 1981-1982 Class B Results. SERI/SP-281-1847, Golden, CO: SERI.

Tsongas, G., J. Peterson, M. McKinstry, and P. Gillen, 1983. Measured versus SLR-predicted performance of a monitored direct gain home, In Proc. of the 8th National Passive Solar Conf. Sept. 7-9, 1983, Santa Fe, NM. Boulder, CO: ASES. pp. 321-326.

Passive Solar Journal, 3(1) 99-104 (1986)

Opinion

Passive Solar Sunset: Predicting Our Own Demise

Murray Milne
Graduate School of
Architecture and Urban Planning
University of California
Los Angeles, CA 90024

Phrases like solar heating, passive cooling, or energy-conserving design should be eliminated as quickly as possible from the vocabularies of all practicing architects. Such phrases should be replaced by the phrase "competent design" and simply taken for granted.

Every client has a right to expect these features from a qualified professional just as they expect a structurally sound, fire-safe, and weather-tight building. In times past, indigenous builders knew very well how to design thermally efficient and energy-conserving buildings. They may not have understood the theory behind their designs, but the rituals, traditions, and cultural taboos governing their work embodied wisdom gained over the centuries. The elegance and thermal ingenuity of these buildings are still admired by even the most high-tech, post-modern architects of today.

Copyright © 1986 by Marcel Dekker, Inc.

For these so-called primitive builders this knowledge of design was crucial because acquiring fuel consumed a huge percentage of most households' resources. In many cultures, at least one member of the family had to devote full time to gathering firewood or dung. In today's dollars that effort would represent roughly $7,000 of potential earnings, only to provide cooking and space heating at a level we would consider quite unacceptable. It is therefore easy to understand the incentive for building good passive solar buildings; families who did not certainly suffered.

During the last hundred years or so the developed countries of the world went on a fuel binge when the relative cost of energy became almost insignificant. Consequently, the last four or five generations of architects have forgotten, little by little, how to design energy-efficient buildings.

The relative cost of energy has begun to creep up again, and now we find ourselves making up for a century's worth of lost research and development. Some of us are also trying to instantly change the priorities and biases of a profession full of designers. Today we obviously need phrases such as passive solar design, but we hope it won't be too long before they become redundant.

How can the importance of these issues be instilled in today's practicing architects? One could argue that it can't. If it took five generations to unlearn this awareness, clearly more than one generation may be required to relearn it. In fact, many of today's architects will probably never fully understand the theory involved; like their ancient predecessors, they may only be able to copy new patterns, prototypes, or styles, or, in other words, new rituals and taboos.

Conceding the difficulty of changing the methodology of long-established professionals, one concludes that students in architectural school constitute the best targets for initiating change. Many good resources are available for this effort, including some fine books by Balcomb, Givoni, Mazria, and Watson, to name only a few. We also have some good buildings to act as precedents. And we have some new design tools available to help with the added complexity associated with this new set of responsibilities.

The most striking difference between practitioners and students today is that the first generation of computer kids are now beginning to graduate. They are totally at ease in the world of computerized design tools. They take for granted electronic arcade games, powerful home microcomputers, and exotic three-dimensional color graphics. For the architectural profession this change in medium from velum to CRT screen will evoke fundamental upheavals far more profound than any of the previous changes from papyrus to linen to velum. Can you imagine a future in which every architect will not have at hand a sophisticated computer graphics terminal?

So what will this new electronic medium be able to do? Certainly it can do far more than simply speeding up what we can already do by hand, although the implementation of existing hand-tools is a worthwhile first step. Clearly this new medium creates opportunities to do new things that were never possible before. I offer the following thoughts:

"Smart" Design Assistance:

Architects would like to use their computer in the same way they would use a good junior design assistant, namely by describing a few preliminary ideas about the building in a very general way, and expecting to get back a very sophisticated analysis almost immediately. The architect needs only to look at this analysis for a few moments before deciding what kinds of design revisions the assistant should make. In this situation, a "smart" assistant must initially be able to make some good assumptions, to create good hypothetical design solutions, and to fill in missing pieces of information where necessary. This leaves the architect free to perform higher level decision making, more like a job captain or chief designer.

Computer-Aided Energy Conserving Design:

The key to developing a useful computer-aided energy conserving design tool is to recognize that most of the decisions that affect a building's ultimate energy consumption are made by the architect at the very beginning of the design project. This is the schematic design phase, the time when the client's requirements must be translated into the first rough sketches showing building geometry, orientation, facade articulation, window treatment, sun protection, and roof configuration. This is also the time when the building's formal vocabulary is elaborated with berms, verandas, atria, courtyards, sawtooth roofs, clerestories, winter gardens, and so on. This, too, is the time when fundamental commitments are made to attempt to utilize passive design strategies such as natural ventilation, daylighting, thermal storage, night flushing, sunspaces, remote storage, or economizer cooling.

At this point in the design process, the architect desperately needs a good, quick, general picture of whether any of these design options make sense for this particular building in this particular climate. Without this information, architects must either guess or be forced to wait until much later to "add the energy concerns" to their design, by which time usually only a few expensive mechanical equipment options remain.

At the schematic design phase, the architect needs only relative energy comparisons or trend information. Refinements and fine-tuning can be left for later stages in the design process. Initially, it is more important to get a rough comparison in a few seconds than to wait hours or days for a precise answer, because when it finally arrives, it will be useless - the building will have been through dozens of design revisions in the interim. The architect needs only design direction. Precise, detailed answers are too complex to be of value at this stage.

Right-Brain Thinkers in a Left-Brain World:

Until now, most interactive computer programs tacitly assumed human users would restructure their thinking to match the computer's method of communication. In fact, computer programmers and engineers find it useful and even quite exciting to try to think through a program in the same way the machine would execute it. Psychologists characterize this as linear-verbal thinking and have shown that it takes place in the human brain's left hemisphere.

Pictorial and graphic concepts, however, are manipulated in the right neural hemisphere. This means that when architects are trying to resolve complex three-dimensional spatial building designs, they are doing a lot of right-brain thinking. The fact that these two modes of conceptualization are so radically different has direct implications for the development of interactive computer-aided design systems.

If a computer program is to communicate with architects effectively, it will have to able to speak their language, in other words, to draw pictures. Admittedly, architects are not totally inarticulate with words and numbers; it is just that they are trained throughout their entire careers to become increasingly sophisticated in graphic communication. This means that an architect can pick up complex information much more quickly if it is presented in a graph, diagram, or sketch than if it is presented as an equation, a table, or a paragraph of text.

This also means that architects are usually more eloquent at drawing than with words or numbers. Unfortunately, today it is extremely difficult for computers to understand the kind of sketches architects like most to draw. So for the present, at

> least, the best compromise in trying to get an architect to "talk" to a computer is to require only the absolute minimum of words and numbers. One way to do this is to write a "smart" computer program that is very good at anticipating what is on the architect's mind. This kind of program requires a "nudge" here and there to keep it headed in the desired direction.[1]

Whatever new design tools are developed for and by this new computer-generation of architects, they will undoubtedly be as user-friendly and self-instructional as current video games. First-time users will be able to operate them with no special training. The communication will be immediate and direct without intervening jargon or off-line operations. The designer will not need to deal with the theory of passive cooling, but simply be able to recognize what constitutes competent performance. Because the user's skill level increases with practice, such design tools must be able to accommodate increasing complexity in order to intellectually challenge and stimulate even the most sophisticated architects.

The research agenda for the coming decade then, I feel, is to translate our esoteric knowledge of passive solar design into a medium that is accessible and user-friendly to the design community.

---

[1] Abstracted from the author's paper entitled "Ten Principles for the Design of User-Friendly Design Tools," presented at the Conference on Microcomputer Applications for Conservation & Renewable Energy, Tucson, Arizona, February 1985.

Passive Solar Journal, 3(1), 105-111 (1986)

Book Review

Daylight in Architecture

Benjamin Evans. New York, NY: McGraw Hill, Inc.,
1981. 204 pp. ISBN 0-07-019768-7. Hardbound. $29.95.

Daylight in Architecture is successful in meeting the author's goal of making daylighting an accepted practice if inspired readers apply the principles and techniques presented there in their own work. More information may well be needed, but the principles are there.

One of the most important aspects of this book is the presentation of daylighting design as an architectural matter. Books previously available on the subject (notably R.G. Hopkinson's Daylighting, Heinemann, London, 1966) have treated the subject technically. Hopkinson's book is to budding daylighting designers as the ASHRAE Handbook is to beginning passive solar designers, leaving them to build their own bridge between engineering and architecture. Mr. Evan's presentation of principles and concepts important to consider in the process of designing a building is to be applauded. The old dichotomy between art and science, theory and practice, is beginning to be mended.

Evans intends the book to help the daylighting of buildings become the accepted rather than the exceptional practice. This intention is to be carried out by informing architects, building owners, lighting designers, illumination engineers, and design students about the basics and benefits of daylighting. Evans' premise, that quality is more important than quantity and that understanding concepts is more important than finite numerical analysis, is certainly a sound one. And certainly all these aforementioned people will profit from reading Daylight in Architecture. But what is the benefit for the readers of the Passive Solar Journal who are interested in the integration and interaction of daylight with climate-responsive design? As Evans himself asks, "How is daylight to be properly used?"

The topics covered do indeed run the gamut of information needed to accomplish the author's aim of encouraging daylight use in buildings. The chapter titles are descriptive: "The Need for Light," "Daylighting as Related to Other Environmental Concerns," "How Daylight Behaves in Architecture," "The Nature of the Skies," "Evaluating Design Alternatives with Models," "Cost-effective Daylighting Design," "Designs with Daylight: Case Studies." The book focuses on practical matters, but with a regard for underlying concepts.

The practical matters are, for the most part, well discussed. The emphasis on quality versus quantity and the avoidance of technical explanations make all parts of the book equally understandable. The most useful chapter seems to be "How Daylight Behaves in Architecture," including a collection of sketches, photographs, and analytical drawings indicating how daylight is distributed by different physical configurations. The chapter on cost-effective daylighting design is readable and comprehensible, as is the appendix on life-cycle cost-benefit analysis, which gives examples of two different buildings and how trade-offs and evaluations were made.

The most seriously flawed chapter, yet the one with the greatest potential, focuses on daylighting as related to other environmental concerns. The entire chapter is only 18 pages, yet each topic easily deserves a chapter by itself. The practical use of this chapter seems to stop short, with significant practical issues being raised but not answered. For example, some characteristics of electric lighting systems are introduced, but a useful addition would have been the light distribution characteristics of typical electric lighting systems (i.e., different direct and indirect systems) and how they can be combined with daylighting systems as organized in the case study section (sidelighting, skylighting, clerestories, atria, and luminous structures). The natural air-flow section presents useful basic information, but fails to relate it clearly to daylighting possibilities, ending with the statement that "...definitive answers to air-flow problems can be realized only through studies of building models, preferably tested in a wind tunnel." (p. 46). Further references would be extremely helpful in this case. Also, specific questions are raised by the general discussion provided, such as the speed at which air moves to produce comfort, and when air becomes a problem due to blowing papers (p. 42). A table of air speeds roughly indicating various environmental effects (such as minimum for cooling effectiveness and limit of comfort due to blowing papers) would be useful, or a reference to find the information. Although Mr. Evans states that "...windows used to admit daylight are the most logical inlets and outlets for air" (p. 41), openings placed optimally for ventilation may not be located to provide the best daylighting. It can be feasible to fix the glass and provide an operable vent in some other building surface (several interesting examples were built by the Keck brothers). Only three paragraphs are provided on acoustics, which leaves the reader just barely aware of the issue.

In the section on solar energy, the important point is made that "Passive solar energy enthusiasts should exercise extreme caution to avoid providing heat at the expense of visibility." But in other parts of the book, especially the case studies, references to the effects of thermal design in buildings are meager, even sometimes ignored, as in Figure 4-19 (p. 67) where a large skylight located directly over a bed would cause excessive heat loss in the winter and excessive heat gain in the summer (even if the house is located in the "perfect climate"). Some inaccurate statements are made concerning the thermal performance of glazed areas, such as the following statement concerning skylights: "They also admit heat from the sun in the winter, reducing the need for internal heating--which can be significant." (p. 69). However, due to the geometry of the sun's path, horizontal skylights do not pick up much solar heat gain in winter when the sun is low in the sky since most of the low-angled radiation is reflected. They do, however, pick up significant heat gain in the summer when the sun is high overhead and the additional heat is a liability. "A properly designed and utilized skylight system with daylight and heat-transfer controls for both day and night conditions will prove viable on a year-round basis in almost all localities" may be true, but why pay for complicated and sophisticated controls when a simple approach such as south-facing clerestories will do the job well?

Another significant aspect for climate-responsive design is shown in the diagrams on page 61 on the effect of a sloping versus a flat ceiling, given the same area of glass and window height. The illustration clearly shows that the lighting levels are equal in the two sample rooms, which have the same glazing, but the room with the ceiling sloped to the back wall has a much smaller volume. Here is a relevant connection to passive design: the smaller volume can require less heating demand in winter (which may be provided by solar gain through south glazing); conversely, the high flat ceiling provides a high ceiling and space for overheated air to rise away from the occupied zone for hot-humid regions. It would be extremely helpful if these connections could be made.

The chapter on the "Nature of the Skies" is one of two sections where hard data are given: the other is a discussion of Illuminating Engineering Society (I.E.S.) recommendations for levels of illumination. The inclusion of these two sets of data happily eliminates the need to turn to the I.E.S. Handbook as an additional resource to find data as resource material for design studies. Unfortunately, the chapter makes one want to have information in other areas that is not supplied, such as wind speeds, information on the relationship between solar radiation and daylight availability, etc. But maybe the approach taken is appropriate--after all, the book is entitled "Daylighting," not "Everything You Always Wanted to Know About Anything Vaguely Related to Daylighting." But this chapter does point up the spottiness of this approach to the book: it is neither a handbook with all the necessary data and procedures nor a totally conceptual approach with all possible permutations and combinations among daylighting and other architectural design concerns explored.

Some daylight availability data mentioned as currently inaccessible (p. 99) in 1981 are available in 1986, allowing more definitive life-cycle cost-benefit analyses. Sources for this information are the Lawrence Berkeley Laboratory Windows and Daylighting Program in Berkeley, California; the Solar Energy Research Institute in Golden, Colorado; and the National Bureau of Standards.

In the book's mix of principles and practical information, the chapter "Evaluating Design Alternatives with Models" goes furthest in the practical direction with extremely useful information and examples. A couple of points are not entirely accurate, however: "The thickness of the walls of the model is irrelevant since their only function is to restrict the entry of unwanted light and to reflect light from its interior surface as would a full-scale wall. The depth and reflectivity of the window sill, however, is important because of its role in reflecting light into the room." (p. 111). The sides of deep openings around windows reflect light into the room just as window sills do, as well as block some light, providing a baffle-effect when viewed from inside the room. All these effects are worth evaluation during the model study, as are curved shapes which, further on down the same page, are indicted as unimportant. Although they may not affect levels of illumination, they will affect perception of the room and gradation of surfaces, issues covered in "The Need for Light."

The series of 18 daylighting case studies at the end is intended to provide an understanding of how the entire design process can be approached with daylight in mind. The case study examples are grouped according to the daylighting approach (sidelighting, skylighting, clerestories, atria, and luminous structures). The choice of examples is mixed; some buildings from Evans' own consulting practice, some buildings completed, some proposed (the case study of the University of Petroleum and Minerals, Dhahran, Saudi Arabia, would fit better in the modeling chapter). The mix of periods and styles shows convincingly that daylighting principles and practice transcend style. However, having a consistent format would help tremendously in explaining the essential features of each building. For example, including an exterior photograph, plan, and section at the same scale; interior photographs; and sketches of significant details would have constituted a full complement of comparative data for expert and layperson alike. It would have been a wonderful climax to the material presented in earlier sections if that information could be integrated here in a consistent commentary on the relationships among daylighting, electric lighting, visual and thermal comfort, and acoustics. The commentaries are too brief for the most part, as are the presentations of the buildings. The case studies do not integrate all the issues presented earlier as completely as might be wished.

Some extremely good points are left hanging because illustrations are hard to understand or missing altogether. For example, the illustrations explaining the effect of brightness ratio (p. 15) are poorly labeled: the light source, its relation to the task and surround, and the surround itself, are unclear. All the illustrations are missing for the first example in the appendix on life-cycle cost-benefit analysis.

I must take issue with the following statement in the final section in "How Daylight Behaves in Architecture": "Except for a slight variation in color spectrum, which is for most purposes insignificant, the light from the north sky is no different from that of the south, east, or west sky, except in intensity and contribution from the direct sun. ...The same soft, diffuse daylight condition that comes from the north sky can be achieved with any other orientation and intelligent use of proper daylight controls." (p. 93). The very dynamism and sense of a special place in architecture come from the definition of the quality of light, its color-rendering aspects, and its many effects from sparkling, skittering, shimmering sunlight to dull drab greyness. To alter and control these aspects is of course possible, but to try to do so suggests the engineering mentality of the '50s when anything could be made into anything else, and everything lost its own expressive character. These characteristics of skylight provide some of our major clues for our biological orientation to the exterior environment.

The book is flavored by the knowledge and style of the author. Ben Evans tells it like he sees it, honestly and directly, exercising his wry sense of humor along the way ("Many an architectural design has endured because of the adaptability of people!"). That alone makes the book worthwhile. As William Caudill states in the Foreword, "In a very personalized approach, Ben combines his background in architecture and his consulting experience for some of the country's leading architectural firms, with his scientific and technical expertise to provide the reader with an approach to design for daylighting that should pay off." It is not a complete desk reference, but it is a very good starting point. Since Evans' book is the first to be published in the United States on daylighting in many a year, it is a necessary staple on the bookshelf.

Review by Marietta S. Millet
Department of Architecture
University of Washington
Seattle, WA 98195

Passive Solar Journal, 3(1), 113-114 (1986)

About the Contributors

Ren Anderson is a Staff Engineer at the Solar Energy Research Institute in Golden, Colorado. He also serves as Adjunct Assistant Professor of Mechanical Engineering, Clemson University, Clemson, South Carolina. Ren received his doctorate in mechanical engineering from the University of Colorado in 1983. His special interest lies in free convection, convection in porous media, and mixed convection problems.

Jeffrey Cook, AIA, is Professor of Architecture at Arizona State University where he heads the graduate research program in the College of Architecture and Environmental Design. He has also focused on passive and hybrid solutions to comfort in overheated climates, and has published and lectured widely on architectural, planning, and aesthetic issues of appropriate response to climate, local materials, and skills. He is a recipient of the Passive Pioneer Award of the American Solar Energy Society in 1984 to honor his early and persistent educational activities.

John Duffy received his doctorate in Control Systems Engineering at Washington University in St. Louis in 1974. Currently he is Assistant Professor at the University of Lowell, Lowell, Massachusetts, teaching in the graduate program in solar engineering.

Marietta Millet is an Associate Professor of Architecture at the University of Washington in Seattle. She consults in lighting design and has published and lectured widely on various aspects of daylighting design. She has served on design and research award juries and on the boards of the Passive Division of ASES and the Association of Collegiate Schools of Architecture.

Murray Milne is Professor of Architecture at the University of California at Los Angeles and maintains a small architectural design and consulting practice in Los Angeles. He earned graduate degrees in architecture at University California at Berkeley and engineering at University of Michigan. He is currently developing two microcomputer design tools under contracts with the U.S. Department of Energy and Southern California Edison.

David Odegard received his Masters of Science degree at the University of Wisconsin at Madison with concentration in solar engineering in 1980. He has performed engineering work related to buildings energy systems at Northern Energy Corporation and Vanderweil Engineers, both in Boston. Currently he is the program manager for renewable energy for the Wisconsin Division of State Facilities Management.

AMERICAN SOLAR ENERGY SOCIETY

Susan M. Burley, Executive Director
2030 17th Street
Boulder, Colorado 80302

BOARD OF DIRECTORS

Bruce D. Hunn, Chair*
University of Texas
Austin, Texas

John S. Reynolds, Vice-Chair*
University of Oregon
Eugene, Oregon

William A. Beckman
University of Wisconsin
Madison, Wisconsin

Karl W. Boer
University of Delaware
Newark, Delaware

Francis de Winter*
Altas Corporation
Santa Cruz, California

Fred S. Dubin
Dubin-Bloome Associates
New York, New York

Joe Farber, Ex-Officio
Newport Beach, California

Bion Howard
National Concrete Masonry Association
Herndon, Virginia

Robert W. Jones
Los Alamos National Laboratory
Los Alamos, New Mexico

Sara A. Balcomb, Secretary*
Balcomb Solar Associates
Golden, Colorado

Marvin Van Der Pol, Treasurer*
Solar Energy Research Institute
Golden, Colorado

Edward Lumsdaine
University of Michigan
Dearborn, Michigan

Pamm McFadden
Elements Design Group
Boulder, Colorado

Frederick H. Morse
U.S. Department of Energy
Washington, D.C.

Mike Nicklas
Innovative Design
Raleigh, North Carolina

Paul Notari*
Solar Energy Research Institute
Golden, Colorado

Blaine F. Parker
University of Kentucky
Lexington, Kentucky

Peter Pfister
Pfister Architects
Minneapolis, Minnesota

Bruce Wilcox
Berkeley Solar Group
Berkeley, California

*executive committee member

PASSIVE ARCHITECTURE AND CONSTRUCTION DIVISION

Susan M. Burley, Acting Secretary
2030 17th Street
Boulder, Colorado 80302

BOARD OF DIRECTORS

Pamm McFadden, Chair
Elements Design Group
Boulder, Colorado

Jim Brown, Vice-Chair
Spring Valley, California

Gary Bailey
Innovative Design
Raleigh, North Carolina

John Duffy
University of Lowell
Lowell, Massachusetts

Cris Benton
University of California
Berkeley, California

John Lu
Tennessee Valley Authority
Chattanooga, Tennessee

Polly Cooper
San Luis Obispo Solar Group
Santa Margarita, California

Alex Wilson
A. T. Wilson Associates
Brattleboro, Vermont

Join the

American Solar Energy Society

Help yourself while you help the cause of Solar Energy.

We invite you to become a member of ASES and join other solar professionals united to advance the cause of U.S. energy independence by adoption of solar energy technologies.

Here are some of the services you will come to enjoy as an ASES member:

- Regular forums for the exchange of technical ideas between professional collegues.
- ***Advances in Solar Energy,*** a compendium of the latest R&D developments in solar energy, authored by select ASES members and published annually by the Society for distribution worldwide.
- Two major technical conferences each year (with published proceedings) presented especially for ASES members and offered to them at special reduced prices.
- A quarterly ***Passive Solar Journal*** in which ASES members may publish their ideas and keep abreast of state-of-the-art developments in this field.
- A quarterly Newsletter with a special technical feature in each issue.
- A wide variety of technical publications offered to ASES members at special reduced prices.
- Special committees and councils providing ASES members the means to voice their views and collectively establish positions on given issues related to solar energy.

ASES needs your support. With the world's diminishing attention to renewable energy development, it is more important than ever that our nation's number one professional solar society remain strong. We can make great strides with your help. Show your commitment and join ASES today. Simply fill in the application below and submit it to the **American Solar Energy Society**; 2030 17th St.; Boulder, CO 80302. For additional information call (303) 443-3130.

……

ASES Membership Application

Name ______________________________

Title ______________________________

Company (if applicable) ______________________________

Address ______________________________

____

Please register me as a:

☐ Full Member ASES only ($50)

☐ ASES + ISES* member ($85)

☐ Full member and subscription to *Passive Solar Journal* ($75)

☐ Check enclosed (payable to ASES)

Signature:

____

☐ Visa ☐ Mastercard ☐ AE

No. ____________________ Exp. Date __________

*International Solar Energy Society ASES international affiliate (Dues include subscription to ***Solar Energy Journal***.)

CODEN: PASJDF 3(2) i-iv, 115-212 (1986)
ISSN: 0277-6456

Passive Solar Journal

Volume 3, Number 2, 1986

LIBRARY
BOSTON ARCHITECTURAL CENTER

Heating, Cooling, and Lighting for Buildings

PASSIVE SOLAR JOURNAL

Sponsorship. *Passive Solar Journal* is the official journal of the Passive Architecture and Construction Division of the American Solar Energy Society, Inc.

Indexing and Abstracting Services. Articles published in *Passive Solar Journal* selectively appear in all major indexing and abstracting publications.

Manuscript Preparation and Submission. See inside back cover.

Subscription Information. *Passive Solar Journal* (ISSN: 0277-6456) is published in four numbers by Marcel Dekker, Inc., 270 Madison Avenue, New York, New York 10016. The subscription rate for Volume 3 (1986), is as follows:

Non-Member Institutions	$ 125.00
Society Member Institutions	90.00
ASES Membership Dues	150.00
Non-Member Individuals	47.50
Society Member Individuals	25.00
ASES Membership Dues	50.00

Your order must be prepaid by personal check or may be charged to MasterCard, VISA, or American Express. Please add $12.00 for surface postage outside the United States. For airmail to Europe, add $15.00; to Asia, add $19.00. Please mail payment with order to: Marcel Dekker, Inc., P. O. Box 11305, Church Street Station, New York, New York 10249.

Copyright © 1986 by Marcel Dekker, Inc. All rights reserved. Neither this work nor any part may be reproduced or transmitted in any form or by any means, electronic or mechanical, microfilming and recording, or by any information storage and retrieval systems without permission in writing from the publisher.

Authorization to photocopy items for internal or personal use, or the internal or personal use of specific clients, is granted by Marcel Dekker, Inc. for users registered with the Copyright Clearance Center (CCC) Transactional Reporting Service, provided that the base fee of $3.50 per copy is paid directly to CCC, 27 Congress Street, Salem, MA 01970. For those organizations that have been granted a photocopy license by CCC, a separate system of payment has been arranged. The fee code for users of the Transactional Reporting Service is: 0277-6456/86$3.50.

Contributions to this journal are published free of charge.

Passive Solar Journal

Official Journal of the Passive Architecture
and Construction Division of the
American Solar Energy Society, Inc.

Editor-in-Chief

ROBERT W. JONES
Los Alamos National Laboratory
Mail Stop J577
Los Alamos, New Mexico 87545

Assistant Editor

MELANIE BLAIN
Los Alamos National Laboratory

Production Editor

NANCY S. REECE
Solar Energy Research Institute
1617 Cole Boulevard
Golden, Colorado 80401

Consulting Editor

JEFFREY COOK
Arizona State University

Associate Editors

DENNIS A. ANDREJKO
State University of New York

J. DOUGLAS BALCOMB
Los Alamos National Laboratory

SUBRATO CHANDRA
Florida Solar Energy Center

EUGENE CLARK
Trinity University

JOHN W. HAYES
Marlboro College

MICHAEL J. HOLTZ
Architectural Energy Corp.

BRUCE D. HUNN
University of Texas

DONALD A. NEEPER
Los Alamos National Laboratory

CLAUDE ROBBINS
Solar Energy Research Institute

RICK SCHWOLSKY
Grafton Builders

ROBERT O. SMITH
Robert O. Smith & Associates

AIMS AND SCOPE

The **Passive Solar Journal** is the official journal of the Passive Architecture and Construction Division of the American Solar Energy Society, Inc., the United States Section of the International Solar Energy Society. This organization has sponsored major national and international passive conferences. The **Journal** is guided by a distinguished editorial board, an international panel of advisors, and expert peer reviewers.

The purpose of the **Passive Solar Journal** is to stimulate and support the flow and exchange of research and professional information. The **Journal** is intended to become the archival record and the standard international reference for the field, with principal directions and issues documented in illustrated and referenced presentations. Annual indexes provide detailed cross-reference access. The **Journal** contains full-length articles, book reviews, and opinions that meet the highest standards of verbal and graphic communication. The scope of subject matter is passive solar heating, passive cooling, and natural lighting plus related subjects including the following:

Advanced concepts
Building climatology
Codes and standards
Community planning
Component design
Computer methods
Conservation
Construction details
Control systems
Daylighting
Design tools
Direct gain
Domestic hot water
Earth coupling
Economic analysis
Education
Energy budgets
Energy storage
Evaporative cooling
Historical examples
Hybrid systems
Indirect gain
Indoor air quality
Instrumentation
Integration and optimization
Landscaping
Lifestyles and needs
Market development
Movable insulation
Phase change materials
Photovoltaic interface
Radiation resources
Retrofits
Roof ponds
Selective surfaces
Shading
Simulation
Sky radiation
Solar architecture
Solar greenhouses
Sunspaces
Testing and monitoring
Thermal comfort
Thermal networks
Thermosiphons
Trombe walls
Underground climate
Urban design
User evaluation
Ventilation
Window systems

Passive Solar Journal

Volume 3, Number 2, 1986

Contents

Opinion/A Charter of Regionalist Architecture 115
J. Cook

Evaporative Cooling Using Thermal Storage 125
J. L. Peterson, B. D. Hunn, and J. C. Hedstrom

Building Thermal Monitoring Methods 149
J. D. Burch

Upholstery Textile Performance Following Exposure to Daylight 179
S. Butler and D. Guerin

Daylighting Data Compendium 191
C. L. Robbins and K. C. Hunter

Book Review/Solar Architecture: The Direct Gain Approach 207
J. Reynolds

About the Contributors 211

Passive Solar Journal, 3(2), 115-123 (1986)

Opinion

A Charter of Regionalist Architecture

Jeffrey Cook
School of Architecture
Arizona State University
Tempe, Arizona 85287

DEFINING A REGIONALIST ARCHITECTURE

The term "regionalist" denotes the dominance of regional considerations in designing the man-made environment. All architecture and urbanism by accident of geographic location can be called regional. Regionalist implies a designed fit to region. The regionalist goal is to assure that design is inevitable to a particular region.

[*] This statement was prepared by the organizers of the Passive and Low Energy Architecture Conference (PLEA) held in Venice in December 1985. It provides a context for the revitalized interest in regional architectures that was the theme of the conference and is an issue of increasing international urgency. While proceedings to be published by Pergamon Press document the formal content of presentations that included both conceptual and technical papers, this charter attempts to outline critical discussions not otherwise represented. International endorsement, translation, and circulation of this document by leading architects who participated in PLEA 1985 is intended to further the issue of regionalism in architecture.

Architecture becomes regionalist when designed to respond to local, natural, and man-made place. Place is an expression of integrated ecologies of climate, resources, and culture. Resources include human skills, intelligence, and persuasions as well as the capacities of the earth at its surface and in its depths.

As in any definition, the perception of edges often becomes the debated issue rather than the validity of the central concept. For instance, the phenomena of architecture and urbanism are usually recognized by the location and condition of their edges; rather, they might be considered by some other measures than the lineal diagrams of plans, facades, or circulation patterns.

Natural places or ecological provinces seldom have crisp edges, except in the case of the seashore. Normally the various zones of a region overlap each other in patterns that require the articulation of human judgment. Thus regionalist architecture may best be appreciated by understanding the normative by focusing on a centroid rather than by characterizing the edges of the territory.

INDIGENOUS SHELTER

Only the Garden of Eden was a neutral place of singular joy. All other places need some intervention, some architectural modification, to make them approach that elusive garden. Whether in single cell shelter or vast geographic landscapes, virtually every human constructive act affects the survival and quality of human habitat.

Regionalist architecture had its preindustrial expression in the time-proven vernacular of indigenous shelter. The rigor of the climate and the limited resources of the land established design parameters for human survival and for human creativity. The snow igloo of the arctic Eskimo is perhaps the most admired both scientifically and intellectually. But, too often such examples of uncanny brilliance are appreciated only as picturesque relics, romantic projections, or refined products of some limited technology, rather than as pivotal human solutions that embody cultural persistence across time. A snow igloo survives at most for one winter season, but it is a timeless, resilient, cultural expression. Although it self-destructs without a trace, it is the epitome of architectural resistance.

The arctic represents a diagrammatically simple condition of climate and culture; only one winter bioclimatic condition exists--very cold, windy, and dry--and only one material is available for construction--frozen snow. Similarly, in many tropical areas the annual bioclimatic conditions are also very stable. Human needs are simple and resources ample, so successful indigenous housing solutions are thereby simple and similar.

Yemen demonstrates how human interventions can develop the culture and resources of a distinctive region with a variable climate. The man-made environment in Yemen is rooted in and reinforced by the continuities of mud architecture--always similar, but never the same--persistent in principle, evolving in the subtle variation of constructive and expressive detail. The plasticity of these earthen buildings allows a well developed aesthetic and symbolic response. Within that rich domestic architectural expression is a variety of alternate configurations that each respond to a particular climatic impact. Here spatial redundancy and internal migration as well as seasonal nomadism resolve the biological contradictions of a multiseasonal climate.

The most complex climatic regions are in the continental and coastal temperate zones where bioclimatic conditions have strong seasonal changes, and where other resources often have unpredictable mixes. Both prehistoric and traditional indigenous buildings usually solved the problem of human environment for only the most critical seasons--severe arctic cold, intense desert heat, heavy rain forest precipitation. Less critical seasons were met with more ad hoc solutions such as the sod lean-to for the arctic summer and roof-top sleeping for hot desert nights. But the sophisticated resources of post-industrial societies should temper multiseasonal problems by bioclimatic designs, such as kinetic envelopes.

CONSERVATION OF RESOURCES

The conservation of resources was one distinguishing aspect of all preindustrial production, whether of products or buildings. The discrete transformation of energy and the preservation of wealth were principles in all cultures that flourished. All creative activity by definition attempted to heighten the conversion of raw materials by respecting conservation. All lasting objects embodied and communicated that concept.

Today conservation seems a novelty. Energy as a concern for architects was only a brief blip. Today the Btu and the megajoule have little appeal to architectural conscience or intelligence. Yet the physics of heat transfer is as fundamental to the genesis of architecture as informed shelter is. Conservation is also the expression of intelligent caring for the future by anticipating the succession of generations. A certain invulnerability is integral to all constructions, but designed resilience is a quality particular to cultural stability.

INDUSTRIAL VALUES

Industrial culture is now characterized by the international trivialization of human life. For instance, the glass box continues to be reproduced as a design solution in all climates and in all locations as a symbol of being modern, an image of technology, and a celebration of irresponsible wealth. An examination of this current architectural artifact from any scientific, intellectual, or experiential criteria reveals how trivial this response is in comparison with known alternatives. The growing dependence on mechanics and plumbers proves how fragile is this tendency toward industrial culture.

THE CONSCIENCE OF VENICE

The positivism and determinism of industrial cultures need a conscience, from the smallest designed object to the largest urban and rural landscapes. Conscience is seldom found in the marketplace. The seeds of conscience are most likely to germinate and thrive in the soils of some cultural regionalism. Venice may be the prototype of such an ecological and cultural regionalism.

Venice is almost unique in the world in appreciating its own regional qualities--an urbane particularness of place and culture. Yet Venice is more than a living museum, more than an artful cabinet of historic remnants. Few other urban centers or regions today value so much their own qualities in the face of multinational commercialism and global media access. Such universal information is not intelligence. Cultural references to place and the matrix of regional particulars are potential antidotes to the arbitrary amnesia of post-industrial trivialization. Authenticity requires roots in the particular. Venice is a noble example of the beneficial continuity of regionalism.

THE THIRD WORLD

The efficient exploitation of all forms of energy (wind, water, wood, fossil fuels, human, and animal) characterizes all regionalist architecture of preindustrial times. That exploitation continues to be the economic and cultural condition of nonindustrial areas of today's world. In the periods before mechanical prime movers--steam engines, internal combustion motors, and electrical motors--conservation of energy was the prime consideration in the making of any artifact--a quilt, a house, a town.

This imperative may be obscured in all cosmopolitan centers today, including those of the third world, where architecture and town building employ the prime movers in the same profligate manner as in the Western industrialized and post-industrial countries. But this form of waste drops off sharply at the edges of cosmopolitan centers even in the West. In the countrysides beyond third world cities, the husbanding of scanty energy sources is a matter of life and death. It continues as the tradition of survival, as the cultural resistance to erasure.

The conservation of cattle dung in India for use as a fuel and as a building material is a constituent fact in a landscape from which wood as either fuel or building material has long ago disappeared. Alternatively, in some rural economies as on the island of Madeira, cattle dung is a critically important fertilizer. In such cultural situations it is a cruel joke for architects and town planners to act as if abundant energy is commonplace. It may never be. In the third world, passive, low-energy designs continue to be mandatory for virtually all structures. Only in such socially desirable megafacilities as irrigation, power generation, and highway construction will it be possible to speak of massive applications of mechanization. The resistance to such massive applications, to which this document refers, must therefore be understood as not merely a sentimental or moral gesture, but as a matter of survival for the regional cultures of the world.

ON THE VERNACULAR

When ancient and vernacular architecture became transformed by regularization of formal schools and books, similar tendencies prevailed as with language. When verbal language became written, and later printed, it successively began to lose the warmth of voice and the personality of hand, as it gained in circulation.

Vitruvius, Alberti, and Palladio identified in classic books on architecture the importance of location and climate. But it was their concepts of a universal building solution and formalized patterns that have triumphed. Oral literature and vernacular architecture may seem anachronisms in an industrial and a post-industrial world. Yet they persist. For all periods local climate and culture are constant generators of original ideas, of vitality, and of the continuities of deep human values.

The results of global industrialization have been different for languages and architecture. Languages have moved toward self-identity on a national or cultural basis, while minimizing the subtlety of local and regional variations. Such related languages as English, French, Italian, and German have retained their own integrity while occasionally informing and enriching each other. Esperanto or some other internationalization has not replaced particular or regional languages.

But architecture has become more internationalized than language. The architecture of public building has begun to make all cities of the world look alike. Architecture has become progressively internationalized by submerging local, regional, and even national characteristics through the free exchange of people, ideas, construction materials, capital, and universal building programs. Yet human needs are not globally interchangeable. Architecture should encourage the differences. And fortunately not everyone wants the same life. Architecture should provide for the distinctions.

FROM PRE- TO POST-INDUSTRIAL SOCIETY

Preindustrial societies only understood themselves in reference to themselves. Culturally they were eco-concentric. Indigenous design solutions were the only solutions. If such solutions were well rooted the culture survived. This continuity had the evolutionary potential for progress and maturity within an integrated man-nature system. Work and life were seldom separated. The home fire was continuously maintained.

Industrial societies explored the planet, exploited remote resources, and expanded the marketplace globally. Culturally they became eco-eccentric. Goods were produced and sold indiscriminately. Similarly, ideas were generated and exchanged. Physical mastery did not imply continuity. Even in the home, when the whole household goes out to work in the morning, and only returns in the night, who maintains the fire? Cultural continuity requires more than a match to relight the fire. The mobile global marketplace by providing the cheapest price has also cheapened value.

In the post-industrial period more human values should prevail. Workplace and home may reunite. The bedroom community, the monocultural neighborhood, and the exclusive zoning of cities will be regarded as outmoded expressions of the industrial period and its production line mentality. A new community and social order requires a new urban expression based on local needs and local preference. The genesis of this new human settlement is the location of the home, which is no longer mandated by the location of work, but becomes a personal environmental choice.

Post-industrialization leaves behind universal access to all goods. Everything available anywhere on earth is not desirable in every specific location on earth. Chinese cookies are stale in Chile. The human program now decreases the emphasis on material goods. Increasingly the direction is toward service. The goal is quality of life, not quantity in life. In a post-industrial society the freedom from material excess still allows and encourages freedom of access to ideas. Now choices are possible in all senses.

REGIONALIST ARCHITECTURE

Regionalist architecture is one of the major opportunities in post-industrial society. It may be the most important, not because it is mandatory in a material sense for survival, but because it is a necessary choice for cultural meaning.

Regionalist architecture is a conceptual paradigm beyond style; beyond photogenic image; beyond romantic illusion; and certainly beyond historicism, revivalism, and academic formulas. The programmatic challenge is to establish local roots that use and express the best of everything that is available. Reference to place is easiest using local resources, materials, and skills. But now the use of all resources, of all choices, is possible. For instance, steel is available globally. Steel is physically the same in Venice, Vence, and Venezuela, and elsewhere throughout our accessible world. But its appropriate use and expression may differ widely even in the same general climate and culture.

Some of the rich architectural possibilities of an international "bioclimatic regionalism" were revealed by the middle of the twentieth century in the pioneering work of the Olgyay brothers and many others. Now in the late twentieth century, the material opportunities are much more comprehensive. However, the non-material need is much stronger. Internationalism as a cultural goal has been found sterile. It is a product of commerce, not culture. At best internationalism is anonymous or neutral. At worst it is man-made environmental pollution that will not go away. It is the universal export that is devastating to local economics and culture.

Regionalist architecture is never neutral since it is rooted in a particular people and place. Its potentials for polarities have yet to be explored. The issue is not whether it is hard or soft, rather, whether it extends particularness. It is an architectural dynamic that creatively includes both self-conscious history and the anonymous vernacular: all the architectures that were indigenous to the place should serve to inspire this new cultural synthesis. Humans build and preserve buildings to preserve themselves, at first in a physical sense, but ultimately in a spiritual sense.

With the tools, techniques, materials, and literacy now available internationally, local values and purposes can finally be served. A new cultural regionalist ethic should inform our intelligence and guide our spirit to celebrate place by restoring our identity.

Endorsed by:

Jeffrey Cook, Arizona State University, Tempe, Arizona, U.S.A.

James Martson Fitch, Beyer Blinder Belle, New York, New York, U.S.A.

Dean Hawkes, The Martin Center for Architectural and Urban Studies, University of Cambridge, U.K.

Sergio Los, Istituto Universitario di Architettura, Venice, Italy.

Natasha Pulitzer, Synergia Progetti, Bassano del Grappa, Italy.

Hasso Schreck, Technische Universität, Berlin, Germany.

Simos Yannas, Energy and Environmental Technology Programme, Architectural Association, London, U.K.

Passive Solar Journal, 3(2), 125-148 (1986)

Evaporative Cooling Using Thermal Storage

John L. Peterson
Bruce D. Hunn
Center for Energy Studies
The University of Texas at Austin
Austin, Texas 78758

James C. Hedstrom
Los Alamos National Laboratory
Los Alamos, New Mexico 87545

Abstract

We assessed the annual cooling energy savings resulting from nighttime evaporative cooling in a small [10,000 ft^2 *(929 m*^{2}*)] office building. We used an hour-by-hour computer simulation to compare the performance of structural mass cooling and evaporative cooling of a chilled water storage tank at night in 11 U.S. climate zones. We studied direct and combined direct/indirect evaporative cooling systems that were incorporated in a variable-air-volume heating, ventilating, and air-conditioning system.*

The results show that cooling energy savings relative to conventional vapor-compression cooling are obtained with evaporative systems in all of the climate zones *studied when thermal mass, preferably in the form of structural mass, is incorporated. The results also indicate that in two of the climate zones studied, conventional cooling can be eliminated entirely by including thermal mass in the evaporative cooling system.*

INTRODUCTION

Evaporative cooling systems used for comfort conditioning in buildings have been the subject of renewed study. In particular, the energy efficiency of multistage combined direct/indirect systems has been shown to be high because of their coefficient of performance (COP) compared to that of vapor-compression cooling (Eskra, 1980). Although most applications are found in the arid and the semi-arid western U.S. climates, these systems have significant cooling potential in more humid climates (Nation, 1984).

Based on research conducted by the Los Alamos National Laboratory (LANL), Peterson and Hunn (1983) assessed the evaporative cooling potential of office buildings in the United States. We assessed direct and combined direct/indirect evaporative systems; however, we did not consider the coupling of these systems to thermal storage. As an extension of this work, we assessed at LANL the performance of evaporative cooling systems using different modes of thermal storage. We investigated the coupling of evaporative cooling systems to structural and remote thermal mass, studying system performance during occupied and unoccupied periods. This article presents the results of that study.

We assessed the performance of alternative evaporative cooling systems for the comfort conditioning of a small office building in 11 U.S. climates. Included in our study were evaporative cooling systems of the direct and combined direct/indirect type that were incorporated in a variable-volume heating, ventilating, and air-conditioning (HVAC) system installed in a single-story office building. The building, consisting of 10,000 ft^2 (929 m^2) of gross floor area, was simulated hour-by-hour for a typical meteorological year (TMY) using a modified version of the PASOLE (McFarland, 1978) thermal network analysis computer program. We defined a base-case building with a conventional vapor-compression cooling system as a reference against which we compared annual energy consumption. We expressed performance results in terms of electrical energy use for cooling.

A significant aspect of this study is a comparison of systems that approach the thermodynamic ideal with real systems that include limitations on storage capacity and its coupling with evaporative system air flows. The study includes a performance analysis of selected thermal storage parameters that spans the range from ideal to realistic engineering assumptions. For operation of the system at night when structural mass is cooled, we compared cases with and without nighttime fan energy. However, we maintained a fixed set of realistic assumptions for the evaporative heat exchange process throughout the study.

APPROACH

Figures 1 through 4 show the performance of the alternative evaporative cooling systems. We simulated these systems using an extended version of the PASOLE (McFarland, 1978) computer program, called EVSIM, for 11 climate regions characterizing cooling zones in the United States. The systems were assumed to operate in a once-through mode (100% outside air), rejecting heat to an ambient wet-bulb resource. To simplify the analysis we did not consider cooling recuperation (Pescod, 1979) wherein the relatively cool air from the conditioned space is returned through the wet side of the indirect evaporative cooler to take advantage of the lower wet-bulb temperature of this air.

Computer Model

McFarland (Jones and McFarland, 1983) developed the basic hour-by-hour computer model. This model treats the multizoned office building as a single zone with four walls and a roof represented as temperature nodes of a thermal network. The mass of all internal surfaces, including the floor, is lumped into a single internal mass node. A minimum space temperature is maintained by the addition of heat from an auxiliary source; the ventilation/cooling system prevents the temperature from exceeding 78°F (26°C). Although the mean radiant temperature can be lowered with structural mass

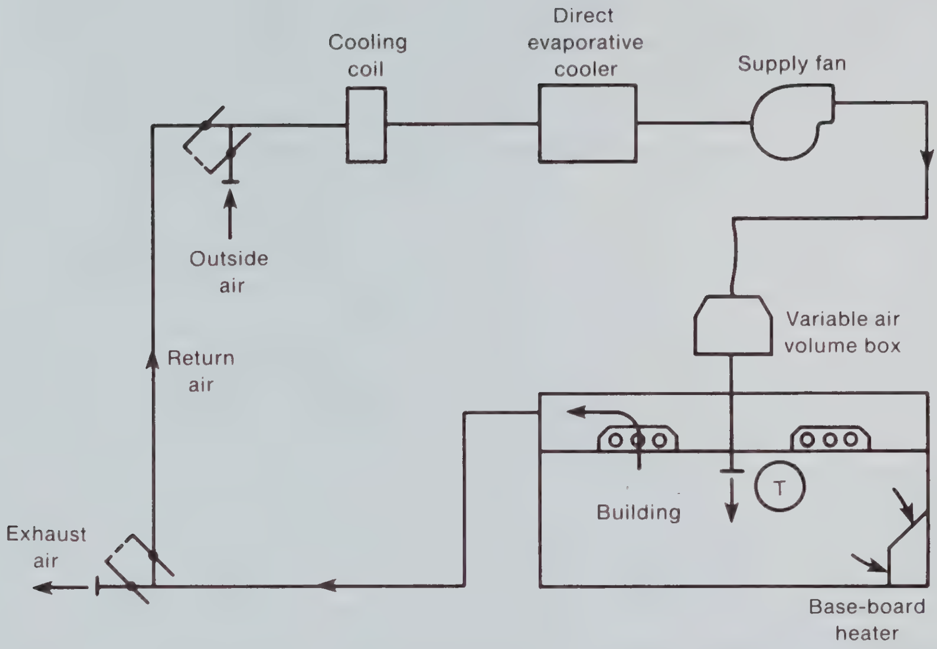


Figure 1. Direct evaporative cooling system

cooling, this temperature depression is not accounted for in the model; the cooling system responds only to the interior dry-bulb temperature. The ventilation/cooling system is represented by a temperature node that is coupled to the room air through a thermal conductance path. By defining this conductance as the product of the ventilation/cooling air flow rate and heat capacity of the supply air flow, the computer program solves for the heat fluxes that balance the thermal network.

We extended the McFarland model to include a subroutine to simulate the evaporative cooling system and renamed the program EVSIM. This subroutine calculates the flow rate and temperature of the air delivered to the space, with cooling provided by either vapor compression, evaporative cooling, or both. In addition, a moisture balance is conducted for the space to determine its dewpoint temperature and latent cooling load. We added a variable-air-volume distribution system with vapor-compression cooling, chilled water storage, and direct and indirect evaporative coolers to the original model.

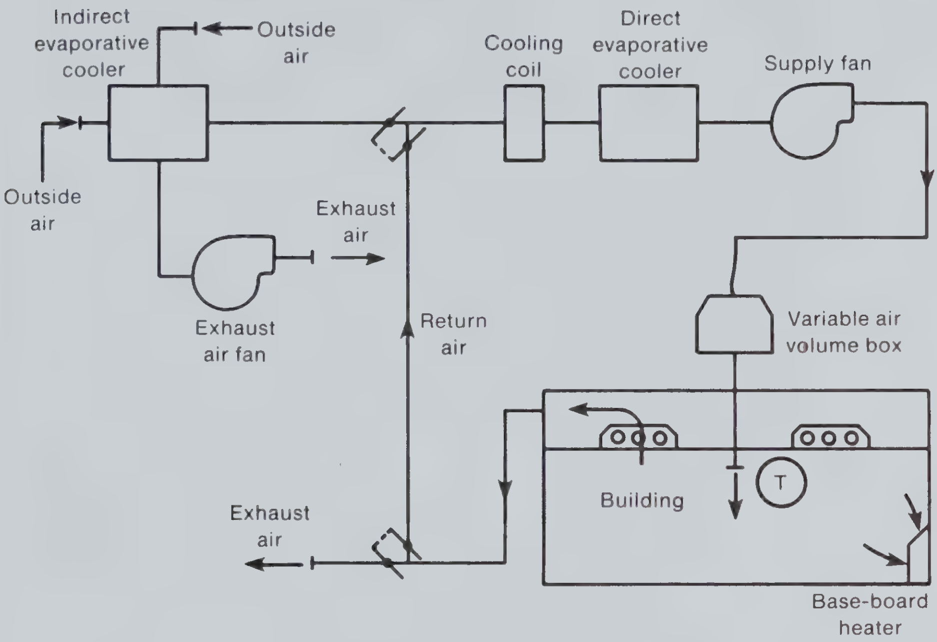


Figure 2. Combined direct/indirect evaporative cooling system

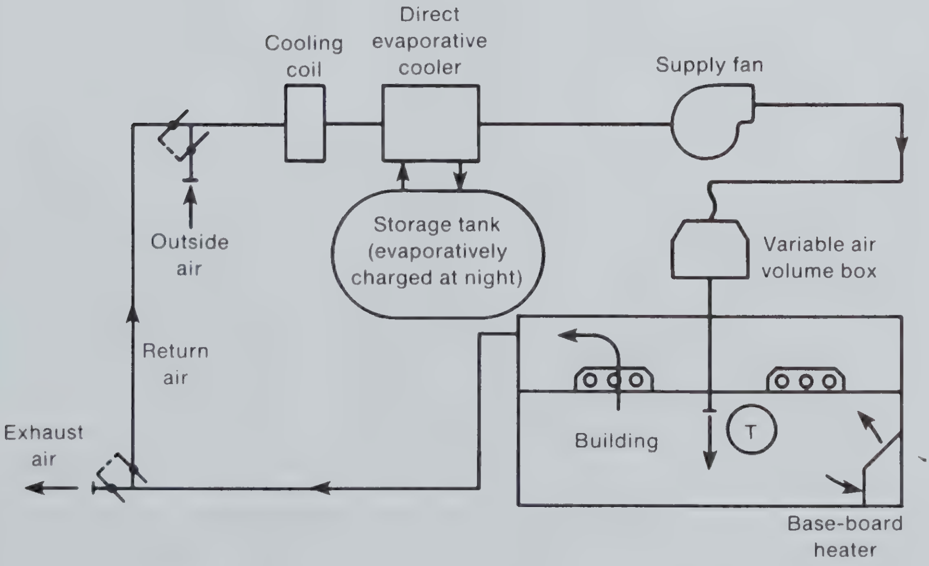


Figure 3. Direct evaporative cooling system coupled to remote mass

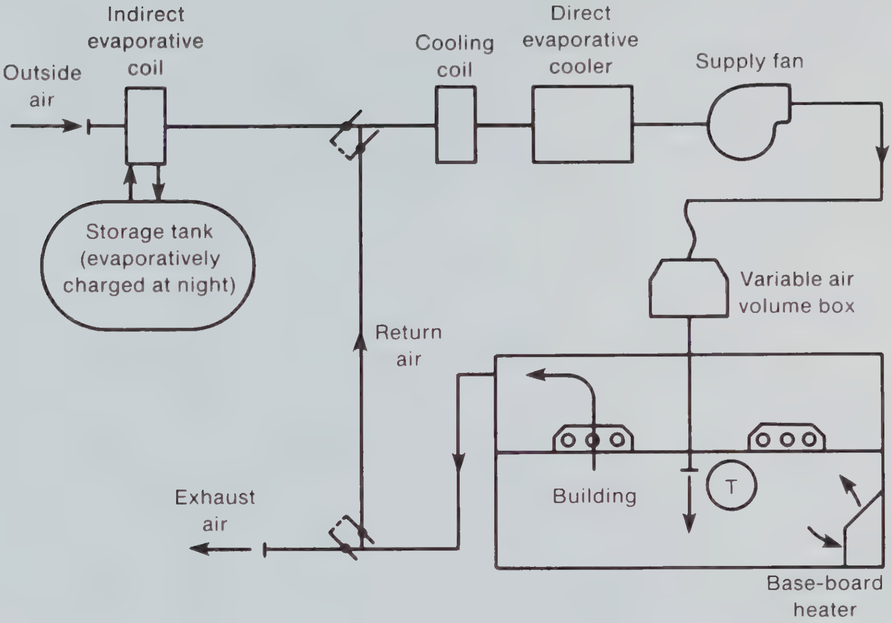


Figure 4. **Combined direct/indirect evaporative cooling system with indirect unit coupled to remote mass**

We modeled the direct and indirect evaporative coolers using a heat exchanger effectiveness. Thus the performance of this equipment is represented by ε, the effectiveness of the heat exchange process

$$\varepsilon = \frac{T_H - T_O}{T_H - T_C} \tag{1}$$

where T_H, T_C, and T_O are the temperatures of the inlet hot fluid, the cold fluid, and the outlet hot fluid, respectively. In the evaporative cooling process, T_C is replaced by the wet-bulb temperature of the secondary air, and the temperature of the primary air entering and leaving the evaporative cooling unit is substituted for T_H and T_O, respectively. The above relationship assumes that the hot fluid has the smaller of the two heat capacity rates $(\dot{m}\ C_p)$. In our model, the direct evaporative cooler is assumed to have a constant effectiveness of 0.85, and the indirect cooler is assumed to have a constant effectiveness of 0.54. This latter effectiveness, which combines the effectiveness of heat exchange on the primary and secondary sides of the unit, assumes commercial equipment with very low parasitic power consumption.

We modeled the hermetic centrifugal chiller performance with the default COP and capacity functions used in the DOE-2 computer program (York, Tucker, and Cappiello, 1981). We increased chiller electric energy use by 30% to account for the power supplied to the chilled water pumps and cooling tower.

Climate Zones

We used 11 regions to describe the range of climate conditions for cooling in the United States [see Andersson, Carrol, and Martin (1982) for the procedure for selecting these regions]. We selected weather parameters to represent the salient climate characteristics of each standard metropolitan statistical area (SMSA) in the United States. SMSAs are grouped to form a region, and the population-weighted regional averages of the climate parameters are used to determine which single SMSA best represents the entire region. Figure 5 shows the set of climate regions selected and the climate center cities chosen to represent each region. We used weather tapes of TMYs for the center cities in the computer simulations.

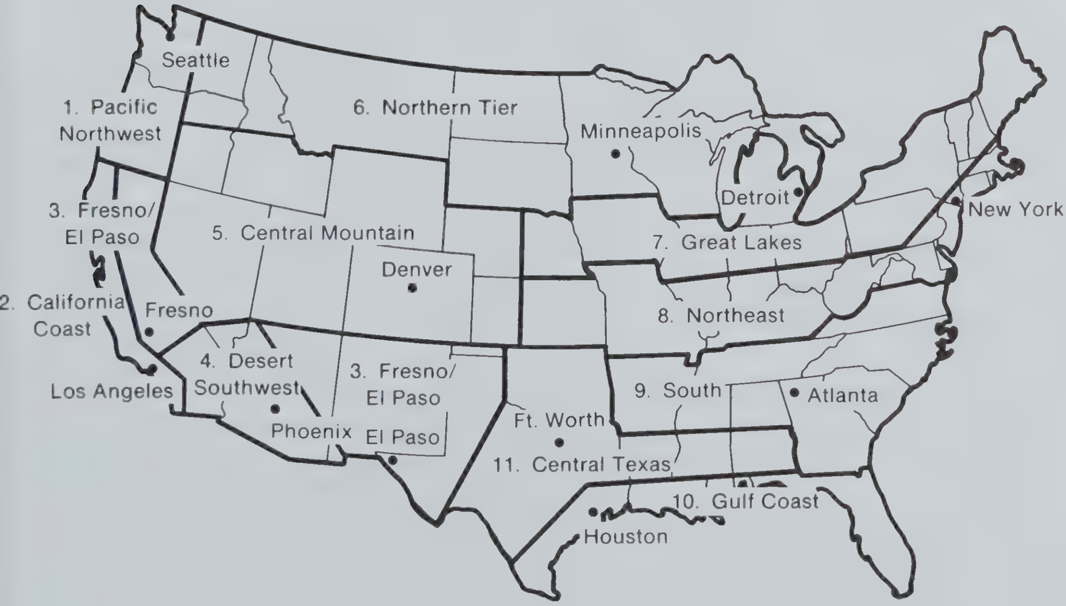


Figure 5. Climate centers and climate regions

Base-Case Office Building

The base-case building is a 10,000 ft^2 (929 m^2) single-story office building with slab-on-grade flooring, 4-in. (10-cm) concrete built-up roof, and exterior walls of curtain wall construction; it is occupied from 8 a.m. to 5 p.m. (see Table 1). A variable-air-volume HVAC system maintains temperatures in the building. Humidity is controlled by providing sufficient conditioned air to the space so that it does not exceed the ASHRAE comfort conditions [62°F (17°C) dewpoint, 78°F (26°C) dry bulb] for more than $2\frac{1}{2}$% of the cooling season hours when the ventilation/cooling system is operated. Design airflow rates are set to ensure compliance with the ASHRAE comfort limit. Once set for the base runs, these design airflow rates were held constant for all subsequent evaporative cooling simulations. A natural gas hot water boiler supplies the heat, which is distributed by a perimeter base-board heating system. A fresh air economizer minimizes the cooling load that is met by the water-cooled hermetic compression chiller serving this building.

Operating Modes for Evaporative Cooling Equipment

The evaporative cooling systems shown in Figures 1 through 4 operate in four modes, depending on room air and outside air conditions. Figures 6 and 7 define the psychrometric boundaries of the outside ventilation air conditions that result in the four operating modes defined below, for daytime and nighttime operation, respectively. We defined these operating modes as a result of our experience in controlling evaporative cooling systems at the Oppenheimer Study Center at LANL (Hedstrom and Murray, 1980). These modes are not necessarily optimal, but they have proven to be practical. Figures 6 and 7 also show control temperatures of interest.

The cold deck temperature T_{CD} is the control point that establishes the supply air temperature. T_{CD} may be fixed or allowed to vary in response to some other signal, such as the room temperature. Because 60% of the heat generated by the lights is vented directly to the return air, the return air temperature T_{RA} is higher than that of the room T_{RM}.

Table 1. Base Case Office Building

- Site: Flat and not shaded
- Building Type: One-story office building
- Building Area: 10,000 ft^2 (929 m^2)
- Building Orientation: Cardinal directions
- Building Aspect Ratio: 1 to 1
- Building Heights:
  - Floor - Floor 12 ft (4 m)
  - Floor - Ceiling 9 ft (3 m)
  - Plenum 3 ft (1 m)
- Thermal Zoning: Single zone
- Exterior Walls: R-14; massless; solar absorptance = 0.5
- Roof: Built-up roofing
  - Solar absorptance = 0.7
  - 4 in. (10 cm) rigid foam board insulation
  - 4 in. (10 cm) concrete [150 lb/ft^3 (2.4 g/cm^3)]
  - R-3 plenum air space
  - R-1.5 ceiling tile
- Floor: Adiabatic; 4 in. (10 cm) concrete [150 lb/ft^3 (2.4 g/cm^3)]
- Interior Walls: None
- Fenestration: 3.5 ft (1.1 m) high along entire perimeter
  - double-pane, 1/4 in. (0.6 cm) - glass
  - solar transmittance (normal) = 0.64
  - overall U-value = 0.57 Btu/hr ft^2 °F (3.2 W/m^2 °C)
- Occupancy: 175 ft^2 (16 m^2)/person
  - 8 a.m. - 5 p.m., Monday - Friday
  - sensible heat gain = 250 Btu/h (73 W)/person
  - latent heat gain = 200 Btu/h (59 W)/person
- Lights: 2.5 W/ft^2; 7 a.m. to 7 p.m., Monday - Friday
  - 0.25 W/ft^2 - otherwise
  - 60% of light energy is vented in the light troffers
- Equipment: 0.35 W/ft^2 - 8 a.m. - 5 p.m., Monday - Friday
- Ventilation: 10 cfm/person; 7 a.m. to 7 p.m., Monday - Friday
- Infiltration: 1.0 ac/h; at all times
- Thermostat Setpoints:

Thermostat Setpoints:	7 a.m. - 7 p.m.	7 p.m. - 7 a.m.
Heating:	65°F (18°C)	65°F (18°C)
Cooling:	78°F (26°C)	Off

- Humidity: Dewpoint = 62°F (17°C) maximum
- HVAC system: Central variable-air-volume cooling
  - Operated from 7 a.m. to 7 p.m., Monday - Friday
  - Perimeter base board heating
  - Static fan pressure = 2 in. (5 cm) H_2O
  - Fan-motor efficiency = 0.34
  - Cold deck temperature = 52.5°F (11.5°C)
  - Variable speed fan
  - Diffuser turn-down ratio = 0.2
  - Temperature economizer set to minimum position above 52.5°F (11.5°C) ambient
  - Water cooling coil
- Primary System: Heating efficiency = 80% at rated capacity
  - Cooling COP = 3.26 at rated capacity of hermetic centrifugal chiller

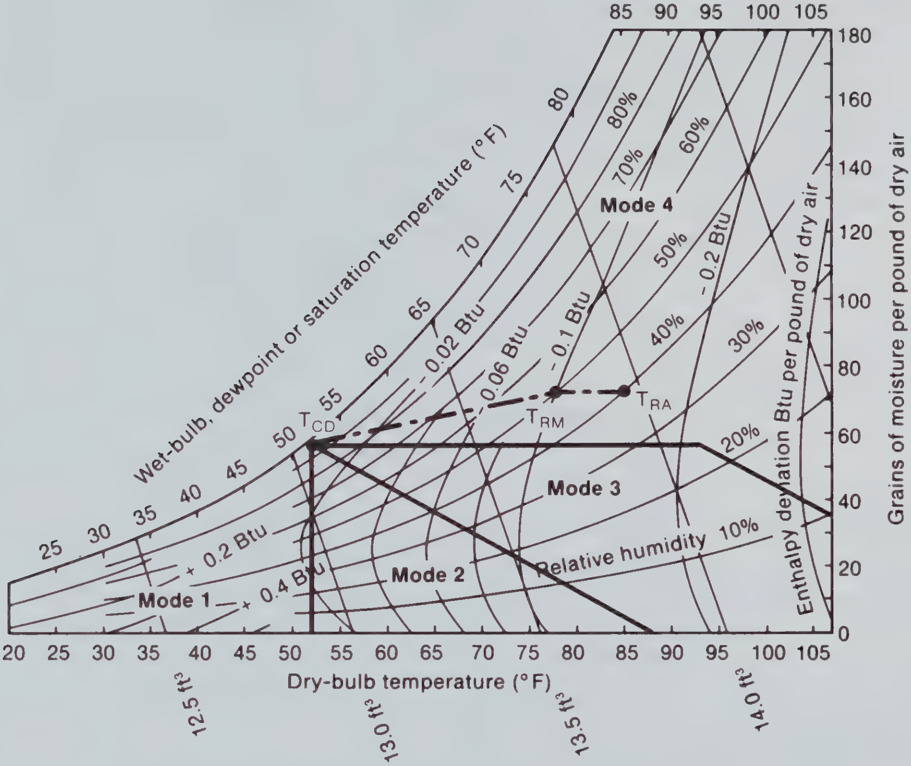


Figure 6. Operating modes for daytime evaporative cooling

Direct System Operation

In Mode 1 operation for the direct evaporative system, the outside air temperature is lower than the cold deck temperature (Figure 6). Outside air and return air are mixed by the economizer damper control to maintain the cold deck temperature. The conventional chiller and the direct evaporative cooling unit do not operate.

Mode 2 is initiated when the outside air enthalpy is below the cold deck enthalpy, but the outside dry-bulb temperature is above the cold deck temperature (Figure 6). In this mode, the economizer control sets the fresh air supply to the full system flow rate, and the direct evaporative cooler is operated. A portion of the supply air bypasses the direct evaporative cooler to obtain the desired cold deck temperature and the conventional chiller does not operate.

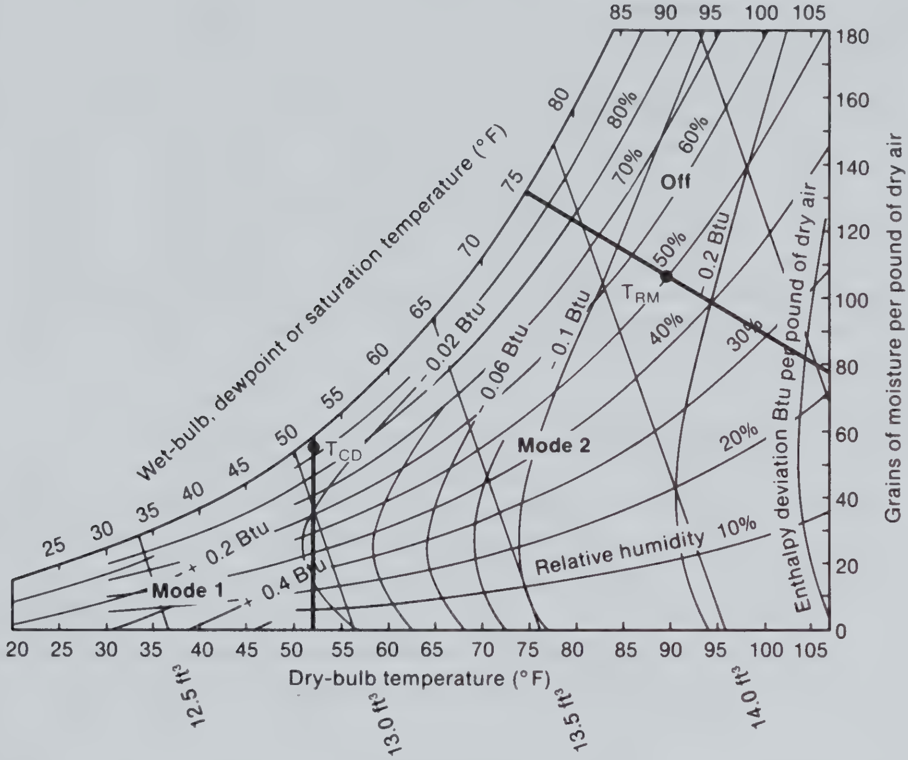


Figure 7. Operating modes for nighttime evaporative cooling

For Mode 3 operation, the outside air enthalpy is below the enthalpy of the return air but above the cold deck enthalpy, and the dew point of the outside air is below that of the cold deck (Figure 6). In Mode 3 the system takes in full outside air. The chiller cools the supply air to the cold deck enthalpy, and then the evaporative cooler cools it to the cold deck temperature. This mode assumes a partial bypass of the chilled water around the cooling coil to maintain the cold deck temperature.

During daytime operation the evaporative cooling system is turned off in Mode 4 because the enthalpy of the outside air exceeds the enthalpy of the return air, or the dewpoint of the outside air exceeds the dewpoint of the cold deck (Figure 6). A preset minimum amount of fresh air is mixed with return air, and the cooling coil is supplied from the chiller to cool the supply air down to the cold deck temperature.

When the evaporative cooling system operates at night, mechanical chilling is not allowed; thus only modes 1 and 2 apply. These modes are the same as for daytime operation except that their psychrometric regions of applicability are defined as in Figure 7. Furthermore, the entire HVAC system is shut down unless the enthalpy of the ambient air is less than the enthalpy of the indoor air (Figure 7). If this latter condition is met, a check is made to determine if conditions for Mode 1 operation are met. If these conditions are not met, then Mode 2 operation is initiated and air is supplied to the space at the same temperature as that leaving the direct evaporative cooler.

Combined Direct/Indirect System Operation

The above description also applies to the combined direct/indirect evaporative cooling systems studied except that for these systems we used the state point of the air downstream of the indirect evaporative coolers, rather than the state point of the outside air, to determine the operating mode. If the mode of operation calls for direct evaporative cooling, then the combined direct and indirect systems are simulated.

Parameters Studied

We made 10 computer runs, described in detail below, for each city to determine the performance of the alternative evaporative cooling systems. To map system performance we studied four key system parameters: heat exchanger effectiveness, thermal mass coupling coefficient, mass capacitance, and energy used to couple the mass to the evaporative system air flow. We calculated the parasitic pressure losses for moving air through the evaporative cooling units and the pumping power to circulate water in these units as described in Hedstrom, Peterson, and Hunn (1985). We included these calculations in the results, except in the runs defined as ideal.

We designed the parametric analysis to exercise each of the evaporative cooling systems shown in Figures 1 through 4 over a wide range of operation, rather than to evaluate exhaustively their performance at intermediate parametric values. Therefore, we assumed a set of real or ideal parametric values for each system that was analyzed. In all cases, we specified realistic values (less than unity) for the evaporative heat exchanger effectiveness. However, we combined real and ideal assumptions for the three mass parameters: the thermal mass coupling coefficient, mass capacitance, and energy used to couple mass. Table 2 shows the values used.

DESCRIPTION OF CASES

We simulated 10 cases to determine the performance of evaporative cooling systems over a range of operating strategies and parameters for the 11 climate zones in the four system configurations shown in Figures 1 through 4. The classification of an operating strategy as real or ideal depends on the assumptions made about the integration of mass with the evaporative cooling system; we classified the operation as ideal if one or more of the three thermal mass parameters was assumed to be ideal (Table 2).

A description of each case is as follows. The cases compare performance of both direct and combined direct/indirect systems with the base-case conventional cooling system; evaporative systems with and without structural or remote mass storage are considered (Table 2). Case 1 is the base case against which we compared the evaporative cooling results. Cases 2 and 3 address the direct evaporative system without and with structural thermal mass, respectively. Cases 5 and 6 are the parallel to Cases 2 and 3 for the combined direct/indirect system. Cases 4 and 7 repeat the structural mass cases, but with the fan power that couples the mass not included at night. These two cases simulate idealized situations in which thermally induced natural ventilation is sufficient to cool the structural mass with evaporatively cooled air. Finally Cases 8-10 address remote (water tank) thermal storage strategies.

CASE 1. Base Case (low mass)

The base case is defined by a conventional vapor compression cooling system that includes a supply fan, chiller, cooling coil, variable-air-volume distribution system, and an economizer admitting outside air when the outside air temperature drops below the cold deck setting of 52.5°F (11.5°C). The air handling system operates between 7 a.m. and 7 p.m., Monday through Friday. The building

Table 2. Evaporative Cooling System Parameter Studies

	1	2	3	4	5	6	7	8	9	10
		Direct			Direct/indirect			Direct	Direct/indirect	
	Base case	Low mass, day	High mass, day/night	High mass, day/night	Low mass, day	High mass, day/night	High mass, day/night	Spray	Coil	Coil, no chiller
Thermal mass configuration	▨	← Structural →						← Remote →		
Heat exchanger effectiveness	▨	0.85	0.85	0.85	0.85 / 0.54	0.85 / 0.54	0.85 / 0.54	0.90	0.85 / 0.80	0.85 / 0.80
Thermal coupling coefficient (Btu/ft^2 h °F)[a]	1.5	1.5	5.0	5.0	1.5	5.0	5.0	∞	∞	∞
Mass capacitance, MC_p (Btu/ft^2 °F)[a]	5	5	30	30	5	30	30	∞	∞	∞
Fan energy at night	▨	▨	Yes	No	▨	Yes	No	No	No	No
Real/ideal classification[b]	▨	R	R	I	R	R	I	I	I	I

[a] Btu/ft^2 h °F = 5.678 W/m^2 °K

[b] Real denotes a realistic assumption or classification. Ideal denotes an ideal assumption or classification.

structure is characterized as low mass, that is, a lumped building heat capacity of 5.0 Btu/ft^2 °F (102 kJ/m^2 °C) (based on gross floor area) and a mass coupling coefficient of 1.5 Btu/h ft^2 °F (8.5 W/m^2 °C) (based on heat transfer area).

CASE 2. Direct evaporative cooling--day (low mass)

This strategy, defined for the system shown in Figure 1, differs from the base case in two ways. First, the strategy considers the effect of the addition of a direct evaporative cooling unit. Secondly, a cold deck reset controller varies the temperature of the cold deck as a function of building temperature from 52.5°F (11.5°C) when the building is at or above 78°F (26°C) to 70°F (21°C) when the building temperature equals or drops below 65°F (18°C). The evaporative unit is available whenever the air-handling system operates (between the hours of 7 a.m. and 7 p.m., Monday through Friday). However, the evaporative unit operates only when the outside air falls within the psychrometric boundaries defining Modes 2 and 3 in Figure 6. These boundaries change as the cold deck temperature T_{CD} is reset. Direct evaporative cooling effectiveness ε_D is set at 0.85.

CASE 3. Direct evaporative cooling--day and night (high mass)

This strategy, also defined for the system shown in Figure 1, extends the operation of the system described in Case 2 to include nighttime operation whenever the temperature of the building exceeds 72°F (22°C) and the outside air falls within the psychrometric boundaries defining Modes 1 and 2 in Figure 7. Also, the building heat capacity is increased to 30 Btu/ft^2 °F (613 kJ/m^2 °C), and the mass coupling coefficient is improved to 5.0 Btu/ft^2 h °F (28.4 W/m^2 °C), which is characteristic of high volume forced convection during the flushing mode. The purpose of these modifications is to determine the potential of flushing the building structural mass with evaporatively cooled air at night. Fan energy consumed at night is included in the calculation. Direct evaporative cooling effectiveness ε_D is set at 0.85.

CASE 4. Direct evaporative cooling—day and night (high mass and no night fan power)

This idealized strategy, also defined for the system shown in Figure 1, is identical to Case 3 except that fan power is set to zero at night. This modification simulates the situation where natural ventilation is used to cool structural mass with evaporatively cooled air at night with $\varepsilon_D = 0.85$.

CASE 5. Direct/indirect evaporative cooling—day (low mass)

This strategy, for the system shown in Figure 2, is similar to Case 2 except that an indirect evaporative cooling unit in the outside air intake is added to provide a second stage of evaporative cooling. Direct evaporative cooling effectiveness is set at 0.85 and the indirect effectiveness ε_I is set at 0.54. The building structure is characterized as low mass, that is, a lumped heat capacity of 5.0 Btu/ft^2 °F (102 kJ/m^2 °C) and a mass coupling coefficient of 1.5 Btu/ft^2 h °F (8.5 W/m^2 °C). Again, the cold deck reset controller varies the temperature of the cold deck as a function of building temperature from 52.5°F (11.5°C) when the building is at or above 78°F (26°C) to 70°F (21°C) when the building temperature equals or drops below 65°F (18°C). The evaporative units are available whenever the air-handling system operates (between the hours of 7 a.m. and 7 p.m., Monday through Friday). However, the evaporative units operate only when the thermodynamic state of the air downstream of the indirect evaporative device falls within the psychrometric boundaries defining Modes 2 and 3 in Figure 6.

CASE 6. Direct/indirect evaporative cooling—day and night (high mass)

The direct/indirect evaporative cooling system operation shown in Figure 2 is combined with the high mass building model described in Case 3 to extend the evaluation of the combined direct/indirect evaporative cooling system strategy described in Case 5 to include nighttime flushing of the building. Fan energy consumed at night is accounted for in this calculation with $\varepsilon_D = 0.85$ and $\varepsilon_I = 0.54$.

CASE 7. Direct/indirect evaporative cooling—day and night (high mass, no night fan power)

The operation of the direct/indirect evaporative cooling system at night to flush the high mass structure (Case 6) is repeated, but the fan power is set to zero at night. This ideal strategy is equivalent to naturally ventilating the structural mass at night with evaporatively cooled air.

CASE 8. Direct evaporative cooling, storage tank (infinite mass)

The direct evaporative cooling strategy described in Case 2 is combined with a storage tank of infinite capacity that is cooled ideally by a cooling tower to the wet-bulb temperature of the ambient air at 5 a.m., without expending any power in the cooling tower (Figure 3). Thus, the ideal potential of this strategy is predicted. Water from this tank is sprayed directly into the air system with the direct evaporative unit during the day, assuming a heat transfer effectiveness of 0.9. This process causes the dry-bulb and dewpoint temperature of the air to closely approach the spray temperature.

CASE 9. Direct/indirect evaporative cooling, storage tank (infinite mass)

This strategy is the same as that described for Case 8, but with two exceptions. First, the storage tank water is delivered to the indirect evaporative coil ($\varepsilon_I = 0.8$ for a multiple-row coil) instead of sprayed directly into the air stream in the direct evaporative cooler. Second, a direct evaporative unit ($\varepsilon_D = 0.85$), similar to the one described in Case 2, provides a second stage of evaporative cooling. In the first stage, the dewpoint temperature remains unchanged and heat transfer takes place sensibly. As in Case 8, the ideal potential of this strategy is predicted.

CASE 10. Direct/indirect evaporative cooling, storage tank, no chiller

This strategy is the same as that described for Case 9 except that no auxiliary cooling is provided (Figure 4). The purpose is to determine if evaporative cooling alone can meet the entire space cooling load without sacrificing occupant comfort.

RESULTS

The results of this study, detailed in Hedstrom, Peterson, and Hunn (1985), provide a large data base from which to draw meaningful conclusions. A summary of these results is presented in Table 3 and in Figures 8 through 12.

Table 3 shows the cooling energy savings calculated for Cases 1 through 9. (Case 10 was not run to determine cooling energy savings so it is not included in Table 3.) A close examination of these results shows that the difference between the energy savings for Cases 8 and 2 is essentially equal to that for Cases 9 and 5. In other words, for remote mass it does not matter whether the indirect unit in a combined direct/indirect evaporative system operates at night; comparable savings are achieved by the operation of the direct evaporative unit alone at night. A similar observation can be made for the structural mass simulations represented by Cases 4 and 7. Obviously, the two-stage evaporative cooling effect diminishes at night as the dry-bulb temperature approaches the wet-bulb temperature.

Figures 8 and 9 present the ideal enhancement of direct and direct/indirect systems, respectively, with remote versus structural thermal mass. Note that the cooling energy consumption for Cases 2 and 5 excludes evaporative cooling equipment pressure losses and recirculating water pump energy so as to maintain consistency among the ideal comparisons presented. The figures show that both structural and remote mass strategies enhance the evaporative cooling potential under idealized conditions. However, structural mass provides the greater savings in most climates, except for direct evaporative cooling in the Pacific Northwest, Fresno/El Paso, and Central Mountain climate regions. Evidently, the lower nighttime ambient dry-bulb temperatures in these regions permit some cooling by conduction through the building envelope without the assistance of ventilation.

Figures 10 and 11 compare the performance of charging a massive building at night for direct and combined direct/indirect evaporative cooling systems under real conditions. Cooling energy savings resulting from the mechanical ventilation of structural mass with evaporatively cooled air are insignificant in most climates and are

Table 3. Annual Evaporative Cooling Enhancement with Thermal Mass

Region	Cooling Consumption[a] Base Building 10^6Btu (293 kWh)	Cooling Energy Saved,[a,b] 10^6 Btu (293 kWh)							
		Structural Mass						Remote Mass	
		Direct			Direct/Indirect			Dir	Dir/Ind
	Case 1	Case 2	Case 3	Case 4	Case 5	Case 6	Case 7	Case 8	Case 9
Pacific Northwest	34.8	18.4 (20.4)	20.6 (24.7)	(26.3)	18.8 (23.1)	20.5 (26.7)	(28.3)	(26.9)	(26.7)
California Coast	92.3	39.2 (41.8)	46.5 (51.3)	(56.8)	39.3 (45.2)	46.7 (54.6)	(59.8)	(51.0)	(50.8)
Fresno/ El Paso	128.4	28.4 (31.8)	31.3 (37.7)	(54.9)	36.8 (44.9)	43.0 (54.1)	(69.2)	(59.7)	(68.7)
Desert Southwest	206.9	38.6 (43.1)	26.3 (35.1)	(67.1)	51.5 (62.5)	49.5 (65.3)	(92.8)	(65.8)	(89.3)
Central Mountain	57.3	23.5 (26.1)	27.8 (32.6)	(38.1)	29.5 (35.3)	32.7 (40.6)	(45.9)	(39.8)	(43.3)
Northern Tier	72.5	14.7 (17.2)	15.4 (20.4)	(28.2)	15.1 (20.6)	16.7 (24.9)	(32.2)	(26.6)	(27.9)
Great Lakes	81.6	15.8 (18.4)	17.5 (22.6)	(31.2)	16.5 (22.2)	19.5 (28.0)	(35.9)	(28.2)	(29.9)
Northeast	75.9	18.5 (21.0)	19.3 (24.3)	(31.7)	18.6 (24.0)	20.5 (28.6)	(35.6)	(27.8)	(29.8)
South	133.9	20.8 (23.8)	19.0 (25.1)	(39.7)	19.5 (26.4)	19.3 (30.0)	(44.0)	(32.5)	(32.6)
Gulf Coast	227.7	22.4 (26.2)	4.1 (12.1)	(38.6)	19.4 (28.4)	2.4 (17.5)	(43.3)	(32.5)	(32.7)
Central Texas	185.4	25.6 (29.3)	13.1 (20.7)	(44.3)	24.5 (33.1)	16.0 (29.8)	(51.9)	(35.8)	(38.7)

[a] Cooling consumption and energy saved include energy delivered to chillers, cooling tower, fans, and cooling water pumps.

[b] Numbers in parenthesis indicate potential energy savings when evaporative cooling parasitics are assumed zero. All other entries represent actual cooling energy savings when these parasitics are included.

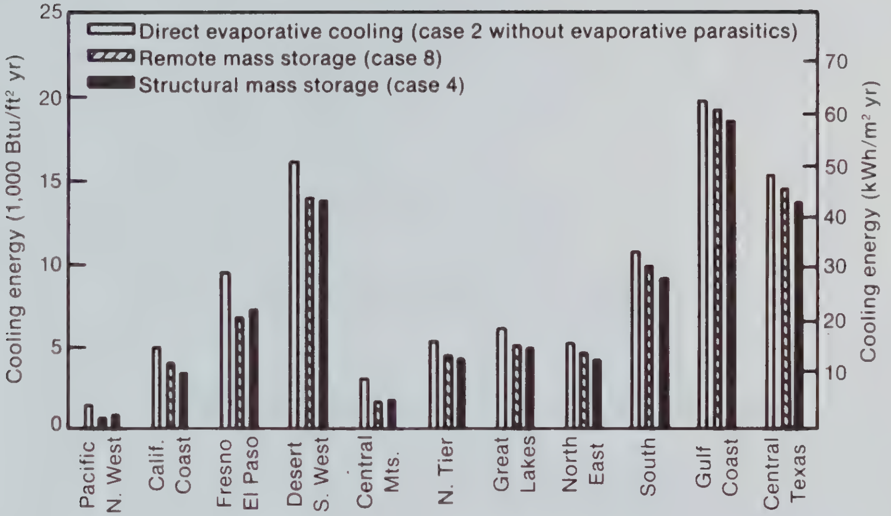


Figure 8. The potential (ideal) enhancement of direct evaporative cooling system performance with remote versus structural thermal mass

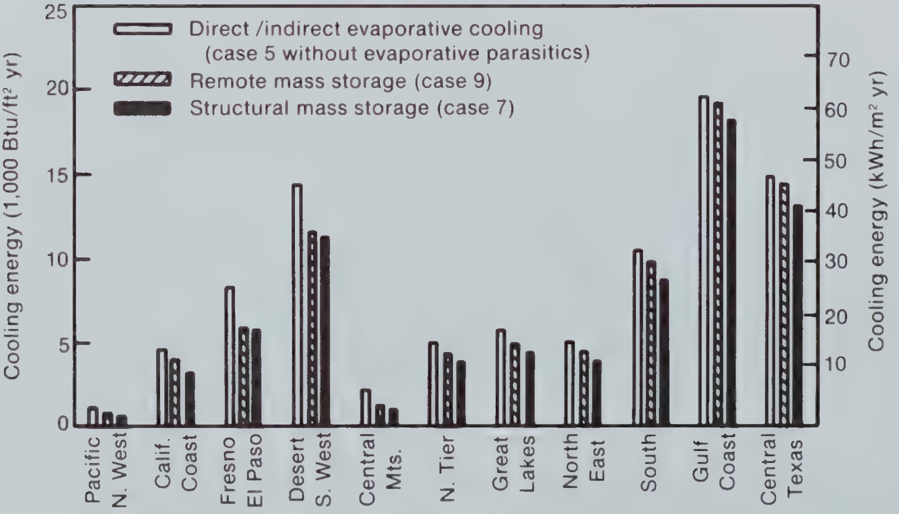


Figure 9. The potential (ideal) enhancement of direct/indirect evaporative cooling system performance with remote versus structural thermal mass

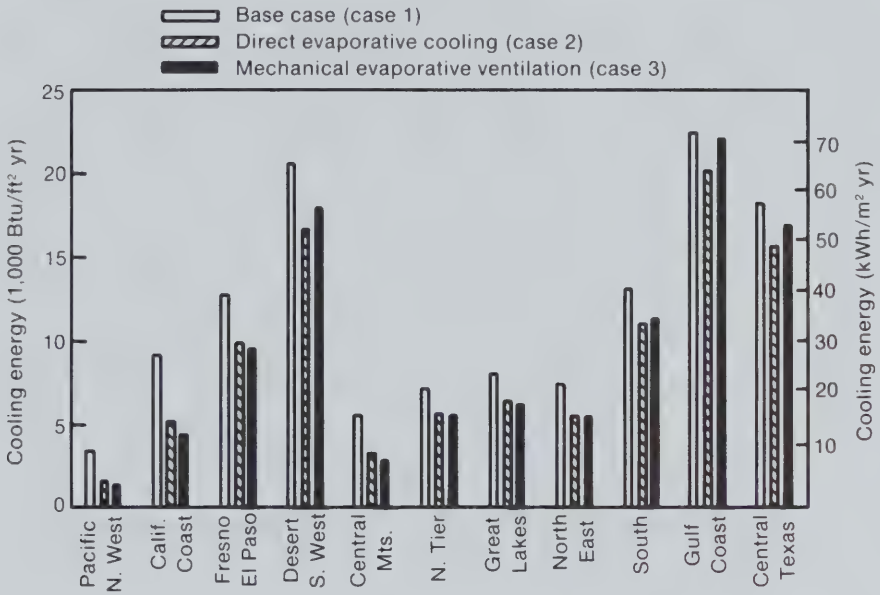


Figure 10. The (real) enhancement of direct evaporative cooling system performance with mechanical evaporative ventilation

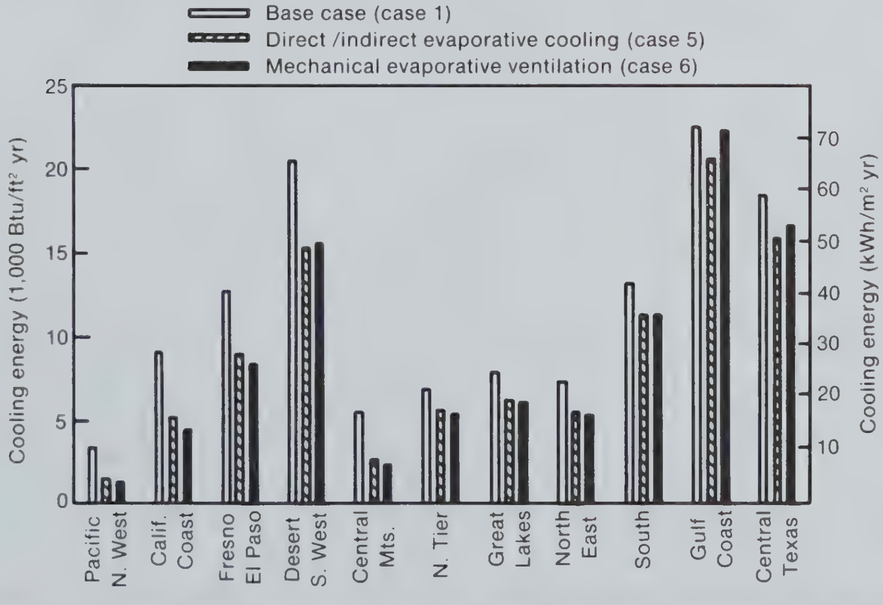
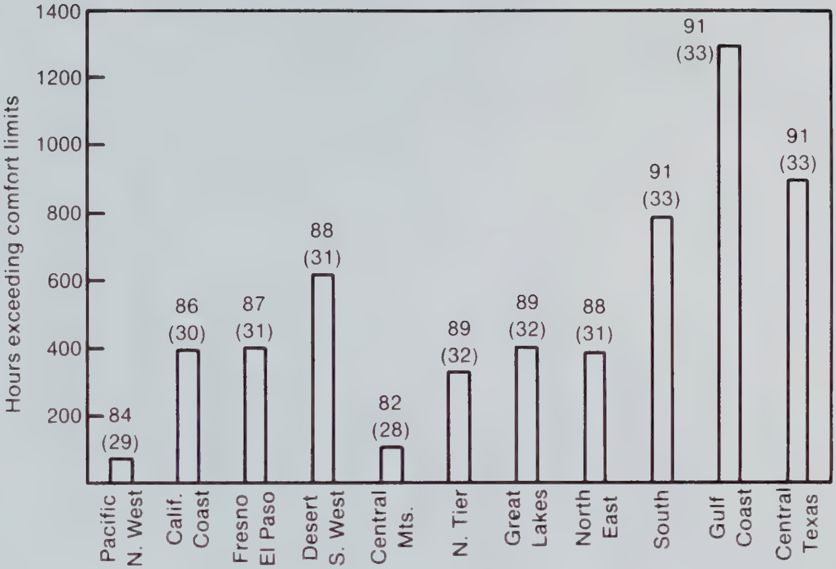


Figure 11. The (real) enhancement of direct/indirect evaporative cooling system performance with mechanical evaporative ventilation



Notes:
Comfort limits are 78°F (26°C) dry bulb, 62°F (17°C) dew point
Numbers shown above the bars indicate maximum building temperature, °F (°C)
Case 10 computer run

Figure 12. An indication of the occupant comfort maintained by evaporative cooling/mass systems without conventional cooling backup

nonexistent in the Desert Southwest, South, Gulf Coast and Central Texas climate regions because the chiller energy savings are offset by the expenditure of fan energy. Therefore, one should avoid nighttime mechanical ventilation in these climates.

Figure 12 shows that for remote mass coupling with combined direct/indirect evaporative cooling systems, only a minor compromise in occupant comfort needs to be made to eliminate mechanical cooling in the Pacific Northwest and the Central Mountain climate regions. The comfort limits are exceeded during hours of occupancy. However, the space temperature never (either in occupied or unoccupied periods) exceeds 84°F (29°C) in the Pacific Northwest or 82°F (28°C) in the Central Mountain region when the chiller is turned off completely. Note that no credit for a mean radiant temperature depression is taken in the cases of structural mass cooling. Furthermore, the results presented in Figure 9 imply that better levels of comfort will be maintained in structural-mass coupled systems as compared to remote-mass coupled systems, because more of the cooling loads are met by the former. Thus, the enhancement of evaporative cooling system performance with thermal mass can potentially reduce electric demand for these two regions of the United States.

CONCLUSIONS

- Evaporative cooling system performance with thermal mass is enhanced more with structural mass than with remote mass.

- The potential savings of cooling energy resulting from the nighttime charging of either structural or remote mass are approximately the same for both direct and combined direct/indirect evaporative cooling systems. Thus, for combined systems it is only necessary to operate the direct evaporative unit at night.

- In some U.S. climates, using a mechanically driven evaporative cooling system to precool a building at night does not result in cooling energy savings. Designers should focus on natural or passive cooling techniques, rather than the mechanically assisted strategies, when considering thermal mass enhancement of evaporative cooling system performance in these climates.

- The coupling of thermal mass, either structural or remote, to the direct/indirect evaporative cooling system of a small office building located in the Pacific Northwest and Central Mountain regions eliminates the need for mechanical cooling while only minimally compromising occupant comfort.

REFERENCES

Andersson, B., W.L. Carroll, and M.R. Martin, 1982. Aggregation of U.S. population centers into climate regions. *Proc. of the Seventh National Passive Solar Conf.* Knoxville, TN, Aug. 30-Sept. 1, 1982, Newark, DE: American Solar Energy Society, pp. 189-194.

Eskra, N., 1980. Indirect-direct evaporative cooling systems. *ASHRAE Journal* 22(5):21-25.

Hedstrom, J.C., and H.S. Murray, 1980. *Solar Heating and Cooling in the Los Alamos National Security and Resources Study Center.* LA-8622-MS, Los Alamos, NM: Los Alamos National Laboratory.

Hedstrom, J.C., J.L. Peterson, and B.D. Hunn, 1985. *A Performance Assessment of Non-Regenerative Evaporative Cooling Systems for Small Office Buildings.* LA-UR-85-1767, Los Alamos, NM: Los Alamos National Laboratory.

Jones, R.W., and R.D. McFarland, 1983. Cooling-load implications for residential passive solar heating systems. *Proc. of the Passive and Hybrid Solar Energy Update.* Washington, DC, Sept. 26-28, 1983. Washington, DC: U.S. Department of Energy, pp. 2-7.

McFarland, R.D., 1978. *PASOLE: A General Simulation Program for Passive Solar Energy.* LA-7433-MS, Los Alamos, NM: Los Alamos National Laboratory.

Nation, J.A., 1984. Evaporative cooling in nontraditional climates. *ASHRAE Transactions 90*, Part 1B:154-165.

Pescod, D., 1979. A heat exchanger for energy savings in an air conditioning plant. *ASHRAE Transactions 85*, Part 2:238-251.

Peterson, J.L., and B.D. Hunn, 1983. Evaporative cooling potential for office buildings. *Proc. of the Second International Congress on Building Energy Management.* Ames, IA, May 30-June 3, 1983, pp. 6.31-6.40.

York, D.A., E.F. Tucker, and C.C. Cappiello, Eds., 1981. *DOE-2 Reference Manual.* LBL-8706, Rev. 2. Berkeley, CA: Lawrence Berkeley Laboratory.

Passive Solar Journal, 3(2), 149-177 (1986)

Building Thermal Monitoring Methods

Jay D. Burch
Solar Energy Research Institute
1617 Cole Boulevard
Golden, Colorado 80401

Abstract

Any method for monitoring building thermal energy has three key steps: model selection, building testing, and model analyses. First a thermal model of the building must be chosen that accounts for all major thermal processes and that adequately answers the questions motivating the monitoring project. Once a model is chosen, a test is designed and executed to determine from data the unknown descriptive model inputs for the building at hand. Tests are either short term (days or weeks) or long term (months or seasons). Lastly, analyses are performed using the model with its measured inputs to provide the desired answers. The calculations made as part of these analyses often involve procedures for normalizing occupancy and weather and for choosing *a reference building. As a general rule, model and test data should be matched on time and space levels. Only several of the many possible combinations of modeling and testing techniques are widely useful. Examples of matching and mismatching model and data are given.*

INTRODUCTION

Although evaluating a building is a multifaceted task involving many parameters, this article considers only the monitoring of a specific building to determine its energy-related thermal behavior. Whole-building thermal evaluation through monitoring is of interest to building owners, energy consultants, designers, scientists, and public officials, among others (Hamilton, 1984). Building owners want to know if their thermal systems are operating properly or if cost-effective opportunities are available to reduce energy costs. Commercial building owners want to corroborate component cost/benefit analyses before planning similar buildings or to rate their occupancy costs for advertising rental space. Building consultants want to determine whether they can recommend cost-effective retrofits or schedule adjustments for improving performance. Innovative designers want to know if the building or mechanical equipment system they designed is performing as designed and the reasons for any discrepancies. Scientific interests include component or model testing and study of specific poorly understood processes such as convection. Program managers of retrofit projects need to unambiguously verify that subsidy of particular measures or designs is justified for reducing peak or average load. These multileveled interests have resulted in a large variety of monitoring methods.

Despite the diversity of these applications, however, whole-building thermal monitoring methodologies have a common structure, as shown in Figure 1. The key element of a monitoring methodology is the thermal model chosen to represent the building. The model must be capable of answering the questions being asked. For example, if a retrofit involves multiple measures that are aggregated by the model, then the individual effects are clearly irresolvable. More specifically, say a greenhouse and a night setback thermostat are installed, and savings from each measure are desired. If a simple degree-day model is used (whose balance point temperature reflects

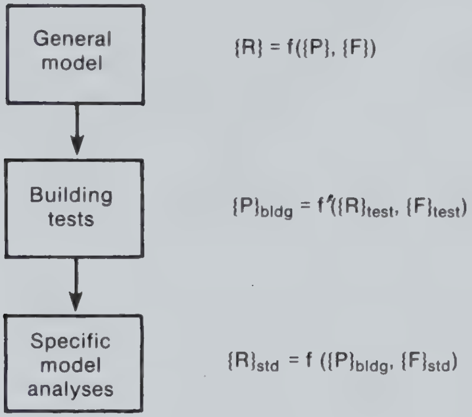

General model
$\{R\} = f(\{P\}, \{F\})$
Building tests
$\{P\}_{bldg} = f'(\{R\}_{test}, \{F\}_{test})$
Specific model analyses
$\{R\}_{std} = f(\{P\}_{bldg}, \{F\}_{std})$

Figure 1. Elements of performance monitoring. The model predicts the building response {R} (e.g., auxiliary) as a function of the descriptive building parameters {P} (e.g., the load coefficient) and the forcing functions {F} (e.g., outdoor temperature). Specific building parameters $\{P\}_{bldg}$ are obtained from measured response $\{R\}_{test}$ under specific conditions $\{F\}_{test}$. Model analyses are then generalized to response $\{R\}_{std}$ to standard conditions $\{F\}_{std}$.

both measures) then the desired result is unattainable. In this case either sequential installation and testing must be done, or a dynamic model must be employed to resolve the two impacts separately. As a more subtle example, a degree-day model should not be chosen for low energy building monitoring since the model is inaccurate in such cases.

In general, models have widely differing space and time resolution. For example, degree day models predict only total consumption over a time period (static), whereas other models can provide hourly resolution of fuel inputs (dynamic). Similarly, some models predict energy fluxes through each element of the building, whereas others only provide total building flows. Models are discussed in the following section.

Once a suitable model is chosen, a building test must be devised to determine the model inputs specific to the building at hand. Tests are analyzed in the section on building testing. The last step in the monitoring is to perform the specific model analyses, in other words, to use the model to answer the questions being asked. Examples are given in the section on model analysis of analysis procedures, focusing on normalization procedures and reference choice. A general rule to follow is that the time and space levels of model and testing data must be matched. Some specific monitoring projects that satisfy or violate this rule are discussed in the section on examples.

Some useful terms are worth defining. Building thermal problems involve three types of quantities: 1) the building thermal system descriptive parameters {P} such as a building steady-state load coefficient, or the mechanical equipment efficiency; 2) the forcing functions driving the thermal system {F} such as outdoor temperature, solar radiation, and internal gains; and 3) the system's thermal response to the forcing functions {R} such as auxiliary energy Q or zone temperatures T. Design and monitoring are the two types of thermal problems, depending on which class of quantities are considered unknown. In the design problem one predicts {R}, given {P} and {F}. In the monitoring problem, the focus of this paper, one first infers unknown {P}, given {F} and {R} during testing, and then calculates {R} under appropriate standard conditions $\{F_{std}\}$.

THERMAL MODELS

Any building thermal model must address the processes shown schematically in Figure 2. Building occupants change some of these mechanisms both systematically and randomly (Kantrowitz, 1983; Kroner, 1983). Models for the energy process in buildings can be categorized according to the the following three time and space levels of the calculations:

> Microdynamic level is a simulation based on solving the coupled equations resulting from applying component-by-component basic heat transfer algorithms (e.g., DOE, BLAST, SERIRES, DEROB) (York and Tucker, 1980; Hittle, 1977; Palmiter and Wheeling, 1982; Arumi-Noe and Wysocki, 1979). Input is a voluminous building thermal description, typically including on the order of 100 parameters for a realistic building. This level is called "micro" because inputs and the calculations are on a much finer scale than the whole building.

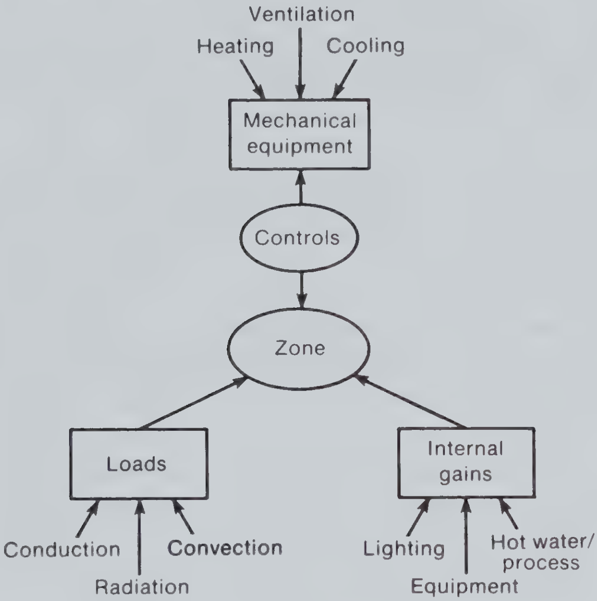


Figure 2. Any thermal model must consider skin loads, internal gains, and mechanical equipment in the analysis

Macrodynamic level is a simulation based on a dynamic whole-zone energy balance. Each thermal zone of the building is described with about 10 "system level" parameters (Sondereger, 1977; Burns, Armstrong, and Winn, 1983; Deberg, 1979; Balcomb, 1983; Jansen and Rasmussen, 1985; Subbarao, 1983, 1984, 1985; Kusuda, Tschiya, and Powell, 1979; Muncey, Spencer, and Gupta, 1970; Madsen, 1983; Subbarao, Mort, and Burch, 1985; Subbarao et al., 1985a&b) which can be regressed from data. This level is called "macro" because both inputs and calculations are on the whole-building or zone level.

Macrostatic level is a simplified, long-term (monthly or seasonal) summary estimate of whole-building consumed energy, based on long-term energy balance, typically requiring about two descriptive building parameters (Oak Ridge National Laboratory, 1980; Engineering Interface Limited, no date; Fels, 1984; DeCicco, 1984; Hirst, White, and Goeltz, 1983; McKinstry, 1983; Kusuda and Saitoh, 1980; Xenergy, Inc., 1983; Rudoy, 1979; Kusuda, Sud, and Alareza, 1981; Erbs, 1984; Bickle, 1983; Building Energy Associates, Inc., 1983; Eyre, 1983; Sullivan et al., 1984; Swisher et al., 1981; Shea et al., 1983). This level is called "static" because of the steady-state form of the basic approach.

These three levels of models are used in both the design and the monitoring problems, as shown in Figure 3. Each level of model directly calculates thermal fluxes and temperatures corresponding to specific levels of the thermal problem data, discussed in the next section. Only the macrodynamic and macrostatic models are widely useful for performance monitoring; these are discussed in more detail below. Microdynamic models have far too many inputs for unique regression from performance data; in principle, such "micro" level inputs can be determined only from component-level data. Because of this fundamental mismatch, microdynamic models are not discussed further.

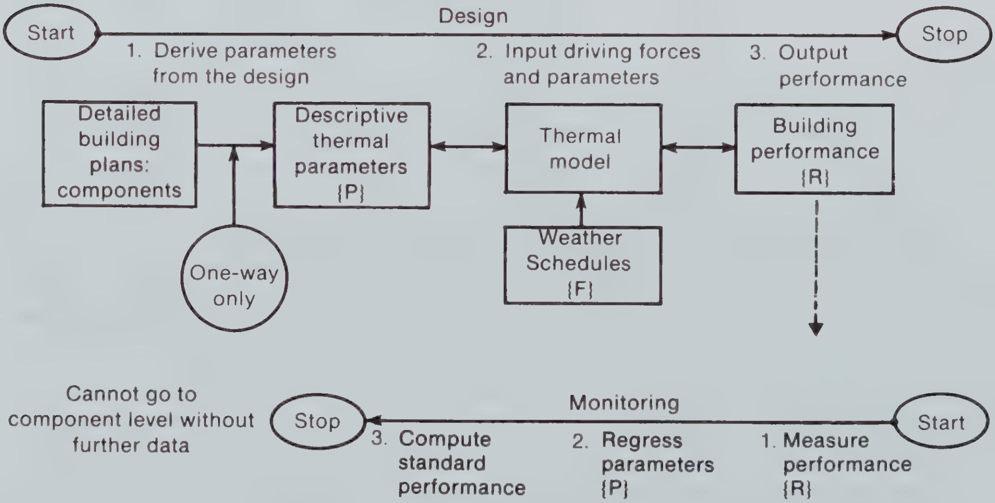

Design
Start
Stop
1. Derive parameters from the design
2. Input driving forces and parameters
3. Output performance
Detailed building plans: components
Descriptive thermal parameters {P}
Thermal model
Building performance {R}
Weather Schedules {F}
One-way only
Cannot go to component level without further data
Monitoring
Stop
Start
3. Compute standard performance
2. Regress parameters {P}
1. Measure performance {R}

Figure 3. The thermal model can be used in either a forward direction (for design) or a backward direction (for monitoring)

Macrodynamic Simulation

Macrodynamic simulations predict the dynamic overall building response {R}, which includes thermal zone temperatures and auxiliary fuel. The methods referenced here have emphasized the skin loads' aspects of the problem, with simple equipment (e.g., constant efficiency) and internal gains models. Only Sondereger (1978) allows explicit separation of ground losses. However, ground coupling and complex equipment models can be included in all the models in a straightforward fashion. Although other approaches are possible, two postulated bases for the models are commonly employed: a thermal circuit that effectively corresponds to aggregated building components (Sondereger, 1978; Burns, Armstrong, and Winn, 1983; Deberg, 1979; Balcomb, 1983; Jansen and Rasmussen, 1985; Subbarao, 1984; Duffy and Puri, 1985); or transfer functions for the response of the thermal zone to relevant driving forces for the problem (Subbarao, 1983, 1984, 1985; Kusuda, Tschiya, and Powell, 1979; Muncey, Spencer, and Gupta, 1970; Madsen, 1983; Subbarao, Mort, and Burch, 1985; Subbarao et al., 1985a&b). The basic forms of these approaches are shown in Table 1. Thermal circuit and transfer function methods are not really different formulations; one can be transformed to the other as convenient, as in Subbarao (1984). However, simple examples in one formulation appear complex in the other.

Table 1. Macrodynamic Models

Thermal Circuit

i^{th} nodal energy balance →

$$C_i \frac{dT_i}{dt} = \sum_j \left(T_j - T_i\right) R_{ji}^{-1} + Q_i$$

Transfer Function

Zonal energy balance →

$$\sum_i Q_{int,i} = \sum_i \int_{t'=-\infty}^{t} h_i\,(t-t')\,F_i\,(t')\,dt' \;,$$

where F_i = forcing function, as T_{out}, I_{sun}, etc.

The numerous thermal circuit references mentioned previously contain simple thermal circuit models, an example of which is shown in Figure 4. Capacitances in these models are effective values that are not directly measurable, are frequency-dependent, and can be difficult to calculate. Another difficulty with most thermal circuit approaches is "cross-talk" (Subbarao, 1984), in which a given parameter affects the building response in different ways depending on the driving force. In Figure 4, for example, the capacitor coupled to the interior temperature node could be determined by a cool-down test, with a nighttime temperature decay providing reliable determination of the parameter. However, that capacitor also affects the response to and storage of solar radiation, which is not part of the postulated testing procedure and hence will most likely be poorly represented. Subbarao (1984) shows a systematic way to avoid cross-talk in circuits, although the circuit contains active elements.

Transfer function methods avoid cross-talk by postulating an independent form for the response to each significant driving function in the thermal problem. Another advantage of transfer function methods is that one can systematically add more independent transfer functions as the thermal problem increases in complexity (Subbarao, 1984; Madsen, 1983). For example, the lights can be the dominant cooling load in a large building. If significant mass is irradiated by these lights, the thermal model must account for the phase lag of the thermal load. The transfer function in response to the forcing function of electricity input is postulated, and parameters would be obtained by a one-time test, expressing both immediate and lagged thermal load. Accurate prediction of these parameters from design plans only is impossible in practice because of the complexity of features such as interior decorations, furnishings, walls, and ballast and light efficiencies.

Macrostatic Methods

Macrostatic or time-integrated methods are based on long-term energy balance assuming negligible change in internal storage, with various simple expressions used for the additive terms in the energy balance. Three related classes of models are degree day, bin, or semiempirical. Mathematical forms of these thermal models are shown in Table 2. Degree-day and bin models are widely used in

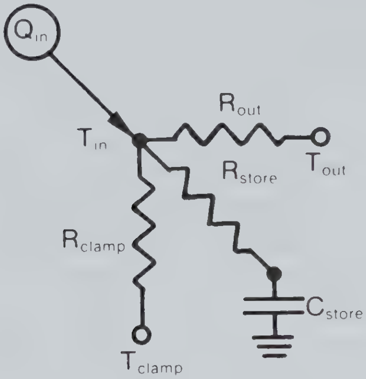


Figure 4. Coupling of inside to outside in this thermal circuit is represented by the pure resistance R_{out}, neglecting mass in external temperature effects. The "clamp" represents an adjacent zone, or the ground. (Source: Sondereger, 1978)

Table 2. Macrostatic Models

Degree-Day Models*

$$Q_{aux} = L \int (T_{bal} - T_{out})^{+} \, dt$$

- Simplistic: T_{bal} = constant
- Variable base: $T_{bal} = \bar{T}_{set} - \frac{Q_{int}}{L}$

Bin Models:*

$$Q_{aux,h} = L_h \sum_{days} (T_{bal,h} - T_{out,h})^{+}$$

Semiempirical Models

$$Q_{aux} = \sum P_i \bar{F}_i$$

P_i = effective building parameter

$\bar{F}_i$ = average driving force

*Note: a plus-sign superscript on parenthesis indicates only positive values contribute to sum or integral.

performance monitoring analysis (Oak Ridge National Laboratory, 1980; Engineering Interface Limited, no date; Fels, 1984; DeCicco, 1984; Hirst, White, and Goeltz, 1983; McKinstry, 1983; Kusuda and Saitoh, 1980; Xenergy, 1983; Rudoy, 1979; Kusuda, Sud, and Alareza, 1981; Erbs, 1984; Busch and Meier, 1984). Usually (Engineering Interface Limited, no date; Fels, 1984; DeCicco, 1984; Hirst, White, and Goeltz, 1983), the balance temperature T_{bal} for the degree-day calculation is treated as a variable extracted from utility billing data, along with the building load coefficient L although this is not essential if only annual savings are of interest (Oak Ridge National Laboratory, 1980). Predictions of variable base bin (VBB) methods are comparable to those of variable-base degree-day (VBDD) models. VBB can more accurately consider some time-dependent aspects not easily treated with VBDD, such as thermostat setback in lightweight buildings, variable ventilation rates, economizer cycles, nighttime insulation, and coincident latent loads. Rudoy's system (Rudoy, 1979) accounts for lags introduced by solar-loaded massive skin walls and will accurately predict savings for a wide range of HVAC system changes. Erbs's method (Erbs, 1984) also explicitly considers solar gains through both apertures and opaque surfaces.

Semiempirical models have incalculable constants imbedded in the postulated expressions that must be determined by regression. Semiempirical linear models used for data analysis postulate the energy balance terms in the form shown in Table 2 with constants of proportionality P_i obtained by fitting the postulated expressions to performance data, such as from utility bills (Building Energy Associates, 1983), daily totals (Eyre, 1983), or from ersatz data produced by component simulations (Bickle, 1983; Sullivan et al., 1984). It is not clear what biases will be introduced in using these models to compute retrofit savings, as the parameters are effective values whose physical interpretation is unclear. This is particularly true as the models admit more and more parameters, such as correspond to coincidence between solar and temperature (Bickle, 1983) or simultaneous heating and cooling (Building Energy Associates, 1983).

In general, the monitoring-oriented macrostatic models should be accurate for energy consumption predictions when the balance temperature is larger than the maximum outdoor temperature, implying that average skin fluxes are linearly related to average temperature differences. When the balance temperature ($T_{bal} = T_{set} - Q_{int}/L$)

approaches the outdoor temperature, requiring consideration of storage and flux lags for acceptably accurate modeling, the long-term models can become inaccurate (Kusuda, 1985). VBDD models must be upgraded to treat most time-dependent strategies, such as night ventilation or economizer cycles. Examples of such upgrading can be found in Kusuda and Saitoh (1980) for night setback and Erbs (1984) for cooling loads. For a number of retrofit measures in lightweight, nonsolar buildings, especially in harsher climates, changes in energy consumption predicted from VBB and VBDD models appear to closely correspond to changes predicted from DOE2.1 component-level simulations, even if the individual absolute values for the two cases were considerably different (Kusuda, Sud, and Alareza, 1981).

BUILDING TESTING

Any monitoring method requires some measure of the building response {R} and the forcing functions {F} driving the thermal response. Building thermal response data can be taken on widely differing space and time levels. The spatial levels, shown in Figure 5, include mechanism, component, zone, submeter, or the master-meter. This hierarchy of spatial detail ascends like a pyramid from essentially unfathomable detail to the simplicity of the readings on a single meter dial. Data on either mechanism or component level are impractical for inclusion in overall building performance monitoring, and their uses are considered elsewhere (Burch, 1984). The building thermal problem also exists on different time levels, dynamic or static, as in Figure 6. Integrated quantities present total consumption, which is sufficient for some people. Dynamic data are rich in cause-and-effect information, containing the fingerprints for classes of thermal processes.

The highest three levels of Figure 5 spatially integrate the effect of all components and mechanisms and are usually called performance monitoring data. The thermal zone data include, for example, zonal air temperatures, radiant or globe temperatures, interior wet bulb temperatures, and delivered thermal energy from auxiliary equipment. The submeter level measures fuel inputs for each major equipment type and other major end use, such as lighting and other equipment, which are actually forcing functions of the thermal problem. Although specifics always vary from building to building,

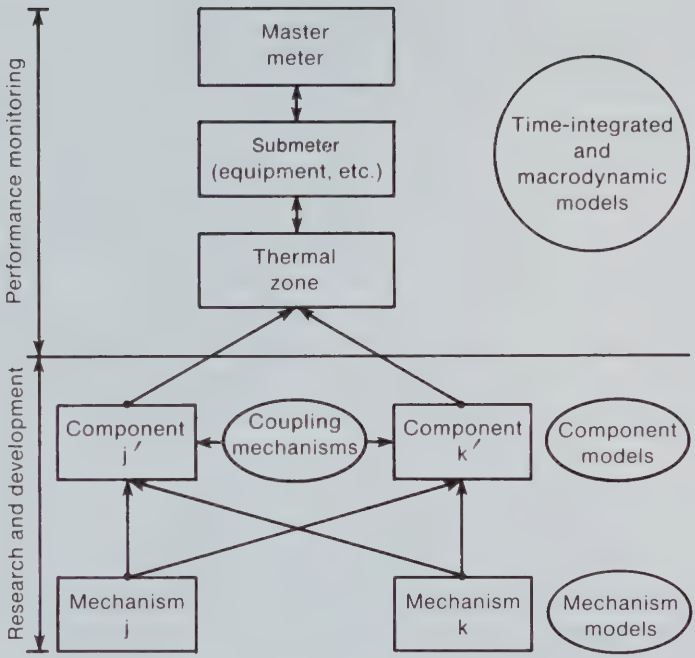


Figure 5. **Monitoring spatial levels. Performance data spatially summarize the effect of many components and mechanisms of energy transport.**

common submetered categories are heating equipment, cooling equipment, air handling fans, lights, water heaters, and other equipment (Ternoey et al., 1985). The last and most aggregated spatial level of the thermal problem, the master meter, measures only the total building fuel input by fuel type. The commercial building electric meter data must include peaks, corresponding to utility demand charges. In several commercial building studies detailed in Ternoey et al. (1985), demand charges average about 75% of the total annual utility bill.

Utility bills are static master-meter data and are commonly analyzed by energy auditors. Dynamic data are rapidly becoming available for several reasons: dynamic electric master meter data are often recorded for demand calculation later (Wright, 1984), dynamic temperature and submetered fuel or status data are already potentially available from a building's energy management system, and suitable data acquisition systems for residential problems can be

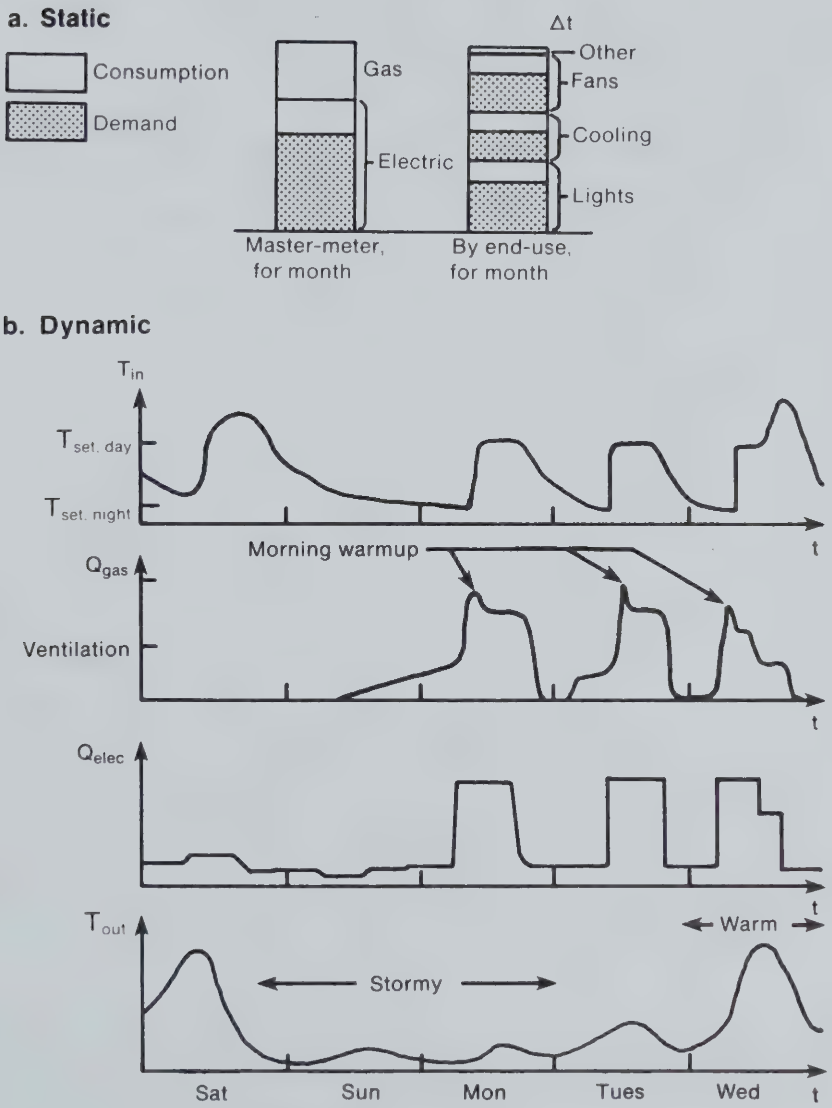


Figure 6. Monitoring temporal levels. Monitoring data can be either static or dynamic.

obtained for as little as $3,000. Master-meter data are a problem if seasonally fluctuating energy for heating, cooling, and ventilation is aggregated with other, nonmetered uses, as for all-electric buildings, or where gas supplies hot water and cooking in addition to heating. In such cases, a disaggregation model is used to separate thermal and nonthermal uses. Disaggregation models for dynamic data are discussed in Wright (1984) and Train et al. (1984). Several references treat disaggregation of static master-meter data (Engineering Interface Limited, no date; Fels, 1984; DeCicco, 1984; Hirst, White, and Goeltz, 1983; McKinstry and Busse, 1983). They commonly assume a weather-independent constant term that must be separated from the weather-dependent heating and cooling term.

Dynamic response data $\{R(t)\}$ are always accompanied by dynamic data on the forcing functions $\{F(t)\}$. Outdoor dry bulb temperature, solar radiation (global irradiance on suitable orientation), and wind velocity are usually necessary. Additional data may include outdoor wet bulb, wind direction, and sky temperature. Dynamic analyses also require dynamic data on the relevant internal gains, which are clearly building-specific. Dynamic monitoring of an office building, for example, might require that lighting and fan circuits, miscellaneous equipment power on wall outlets, and other special concentrated uses (e.g., large computer center or elevator) be metered separately. A dynamic disaggregation model may be used instead of submetering for some cases (Wright, 1984). For static analysis, appropriate temperature and radiation averages over the time interval between the meter-readings must be calculated. Procedures vary between monitoring methods, including direct computation from daily or hourly data, or statistical models requiring only monthly averages (Erbs, 1984).

All monitoring methods require static building information obtained from plans or site visit, such as floor area, equipment descriptions, shading characteristics, and occupancy schedules. Additionally, some may require one-time measurements, such as leakage area and flow rates in pumps or fans.

Building tests can be long- or short-term. Macrostatic tests require long-term testing. Macrodynamic methods have not been successfully used with long-term test data. Short-term tests extend over a period of several days to several weeks; they offer the obvious advantage that the project can be completed in only a few days. Short-term tests can be either noninterventive (Sondereger, 1978; Burns, Armstrong, and Winn, 1983; Deberg, 1979; Subbarao, 1984), or interventive (Subbarao, Mort, and Burch, 1985; Subbarao et al., 1985a&b). In noninterventive approaches, the building is simply observed as it functions normally. Although this approach doesn't disturb the occupants, the results can be ambiguous or erroneous. For example, no degree of sophistication can overcome the impossibility of internal mass characterization if internal temperature is constant during the tests.

Interventive tests can solve some of the difficulties inherent in noninterventive tests. For example, internal temperature changes in response to step or sinusoidal variation in internal gains or equipment operation can be introduced to provide accurate information on mass (Subbarao, Mort, and Burch, 1985; Subbarao et al., 1985a&b). The temperature changes can be small, i.e., a few degrees Celsius. A general procedure for designing interventive tests as a function of model complexity has been given in Subbarao et al. (1985a).

MODEL ANALYSES

A wide variety of analyses can be done with the thermal model using the measured inputs $\{P\}$ to describe the building, and some chosen forcing functions $\{F_{std}\}$ to calculate the responses $\{R\}$ needed for analyses. Actual analyses, of course, depend on the exact intent of the monitoring, and will be specific to each project. Three types of analyses are discussed here: ratings, diagnostics, and savings.

Ratings

A rating is a quantitative indicator of building thermal performance, such as energy consumed for space-conditioning per unit floor area per year. A rating can be future-oriented (will perform) or past-oriented (has performed). The former would be used for advertising or financing purposes, etc., and the latter might be used in identifying potential for retrofit.

A key issue in ratings is normalization of factors such as weather, internal gains, controls operations, and building size. A building's energy consumption, even as observed over a year, is generally unsuitable for a rating because of factors such as unusually warm or cold weather, or atypical operation of the controls.

These normalizations are accomplished by computing under "standard conditions" the space-conditioning energy from the thermal model, whose input parameters {P} have been determined from the building tests. Standard conditions means some combination of the following: long-term average weather [such as in typical meteorological year (TMY) files or 20-year historical records]; demographically typical controls operation (e.g., thermostat practices in Florida differ from those in Minnesota); and demographically typical internal gains. All three conditions are difficult to define and to some extent arbitrary. Except for Busch and Meier (1984), none of the referenced macrostatic methods adjust for standard internal gains or abnormal solar irradiance, although such adjustment is possible.

Building size is usually normalized by dividing annual consumption (total, or subtotals for heating and cooling separately) by floor area. Numerous other indices can also be defined (Loftness and Crenshaw, 1985). For skin-load-dominated problems, an index normalized by weather is defined for heating and cooling as energy per area per year per degree-day. This index is useful only when a degree-day model can be expected to be a good model. A degree-day model would not be appropriate for large commercial buildings in which the weather-normalized index makes little sense because the problem is strongly driven by internal gains and loads will have little relation to degree-days.

Diagnostics

Diagnostics is defined here as a determination of the performance of the thermal system or sub-system. If we consider a new building, for example, the monitoring might be used to determine if the building is performing up to design expections. This can be done in two ways: performance {R} or parameters {P}. In performance comparison, one problem will be that the design study assumed different weather and internal gains than those of the test data. If the design calculations are altered to reflect the actual forcing functions during the testing, we still need to explain the deviations (if significant) between actual and predicted.

The second means of comparison, by parameters, can pinpoint causes of discrepancy. When parameters implicit in the design calculation deviate significantly from values determined by direct measurement, then either the design calculations were in error or the building was not built as specified. For example, the steady-state load coefficient is a parameter in most of the models. An unexpectedly large, steady-state load coefficient is easy to understand in the abstract: anomolous coupling(s) exist to outside air. Missing insulation, inferior construction, thermal bridges, broken or open windows or door, or unscheduled night ventilation are examples of potential causes of such coupling. Engineering acumen is clearly essential in those cases. Some of these possibilities for an anomolous coupling could be eliminated, in theory, by dynamic methods, but there are few examples.

Savings

Savings is the difference in performance between the building of interest and a reference building under similar conditions. The choice of reference is central to the notion of savings, and is somewhat ambiguous. In monitoring retrofits before and after construction, the reference would be the pre-existing building, but detecting or accounting for variances in operating conditions or internal gains, among other factors, is difficult in macrostatic methods. Usually the only normalization is for outdoor temperature. Such difficulties are not encountered in short-term macrodynamic methods, where the same standard conditions will be used in both the before and after simulations, with only the measured building inputs $\{P_{\text{before}}\}$ and $\{P_{\text{after}}\}$ differing in the two simulations.

The reference choice is more difficult to define for determining the savings from a particular component or feature in the building. As in Figure 7, the reference will be the same building with the component replaced by some other section or measure. Obvious choices for savings from a solar aperture are an adiabatic wall, or the opaque wall section used elsewhere in the building. In either case, the reference is an imaginary building whose thermal model parameters have to be calculated. One calculation method is to rely on

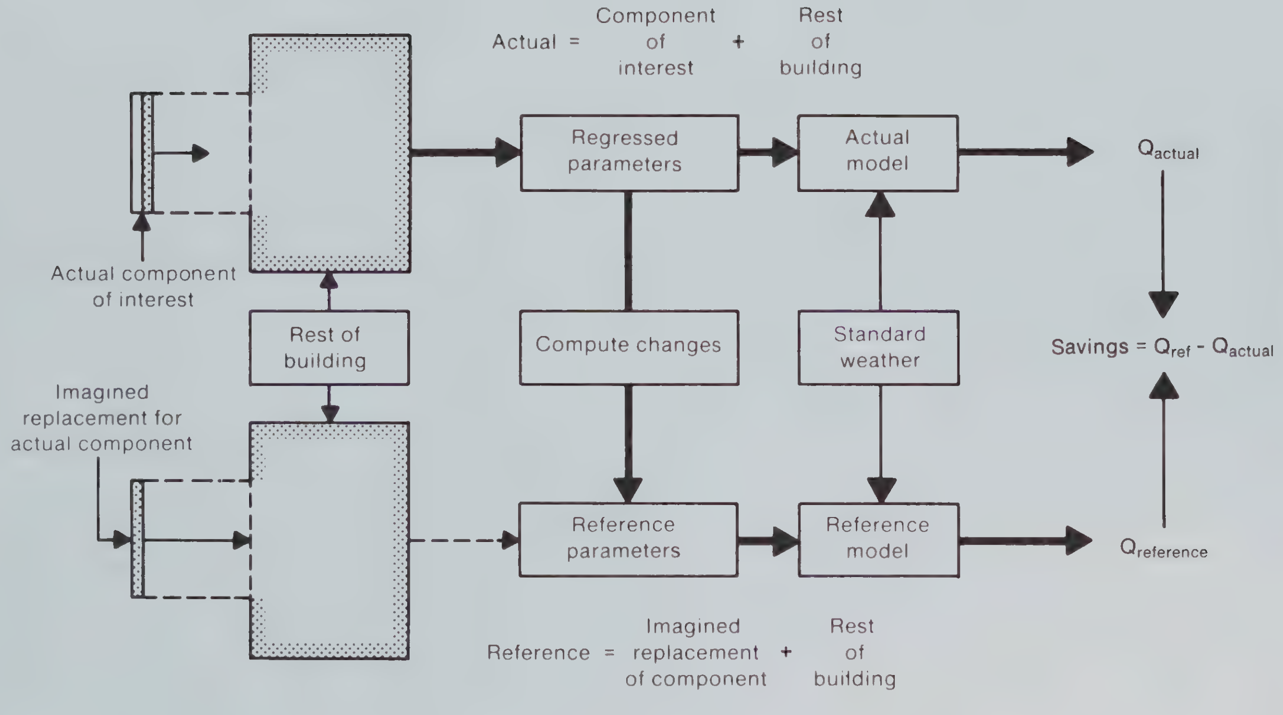

Actual = Component of interest + Rest of building
Actual component of interest
Rest of building
Imagined replacement for actual component
Regressed parameters
Compute changes
Reference parameters
Actual model
Standard weather
Reference model
Q_{actual}
Savings = Q_{ref} - Q_{actual}
$Q_{reference}$
Reference = Imagined replacement of component + Rest of building

Figure 7. Component savings are determined by comparing the annual end-use consumption of two models, one for the actual building and one for the reference building

calculation of only the changes in parameters due to changes from actual to reference building. Thus, the rest of the building is fixed by the testing data, and only the imaginary reference building features are calculated, as in Figure 7.

A GENERAL RULE FOR MONITORING METHODS: DATA-MODEL MATCHING

A critical feature of any scientific theory is the interplay between theory and experiment. In building monitoring this interplay is manifest in that the test data should provide a unique, well-defined set of descriptive inputs {P} for the chosen model. Because of the multilevel character of both models and data (see Figure 8), many combinations of model and data are possible; any data can be linked with any models. However, as shown in Figure 8, the link between model and data is strong only if model and data are matched on the same time and space level. Consequently, only two pairings of model and data are practical, either where both are macrostatic or both macrodynamic. These pairs are shown as the first two levels of Figure 8. Examples of appropriate matching and mismatching are in the next section.

Several additional relationships implicit in Figure 8 are worth mentioning. First, data on higher, more abstract levels cannot possibly provide inputs for a model on a more detailed level (e.g., utility bills can have no bearing on the accuracy of an input for wall conductivity). In such cases the data can provide only a very weak and inconclusive form of validation, indicated in Figure 8 by the dotted lines. Also, note that a complete data set on a more detailed level can always be aggregated in space and time to provide an appropriate data set for a higher level of analysis. Although this aggregation is often done in monitoring, one wonders why data were acquired that are more detailed than needed for the analysis. Examples are given in the next section. Lastly, note that the models should form a self-consistent hierarchy; the inputs to a higher level should be derivable from a given complete set of inputs on some more detailed level of model.

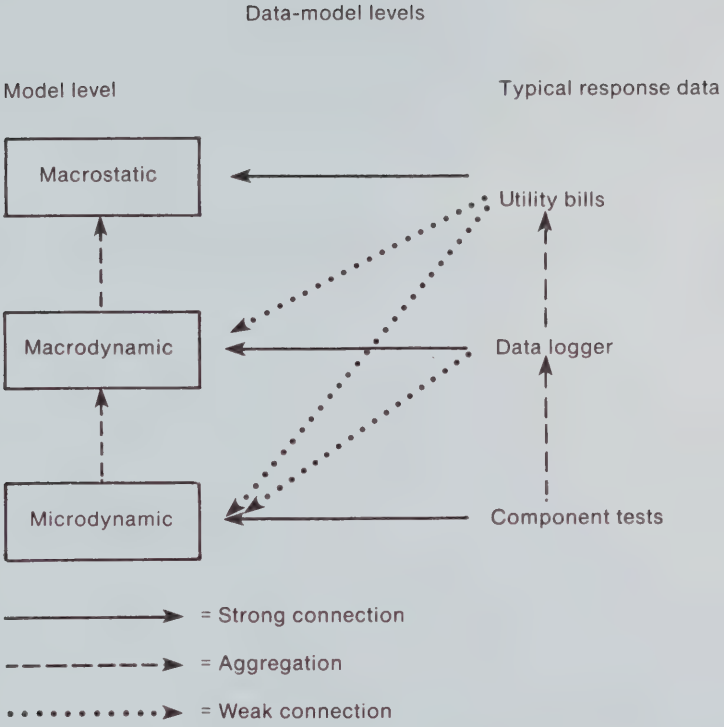


Figure 8. **Levels of model and data. Macrostatic models (macrodynamic models) are strongly linked to macrostatic data (macrodynamic data), as indicated by solid horizontal lines. Weak data-model links are indicated by dotted lines.**

EXAMPLES OF MATCHING AND MISMATCHING

Two useful data-model matches are appropriate for whole-building performance: macrostatic data with macrostatic model, and macrodynamic data with macrodynamic model. Macrostatic models have been well used by industry because the calculations are simple and are known to be applicable to lightweight buildings, and the few intuitive parameters can be regressed from monthly bills. As an example of a well-matched macrostatic method, performance of a 4000 m^2 (43,000 ft^2) multifamily apartment complex was monitored in DeCicco (1984) using monthly, master-meter gas and electricity data, VBDD model, and calculation of weather normalization retrofit savings. Figure 9 shows monthly data (letters) and VBDD fit (line). The measured energy use was much higher than expected from an analysis of the building plans. This was explained by the

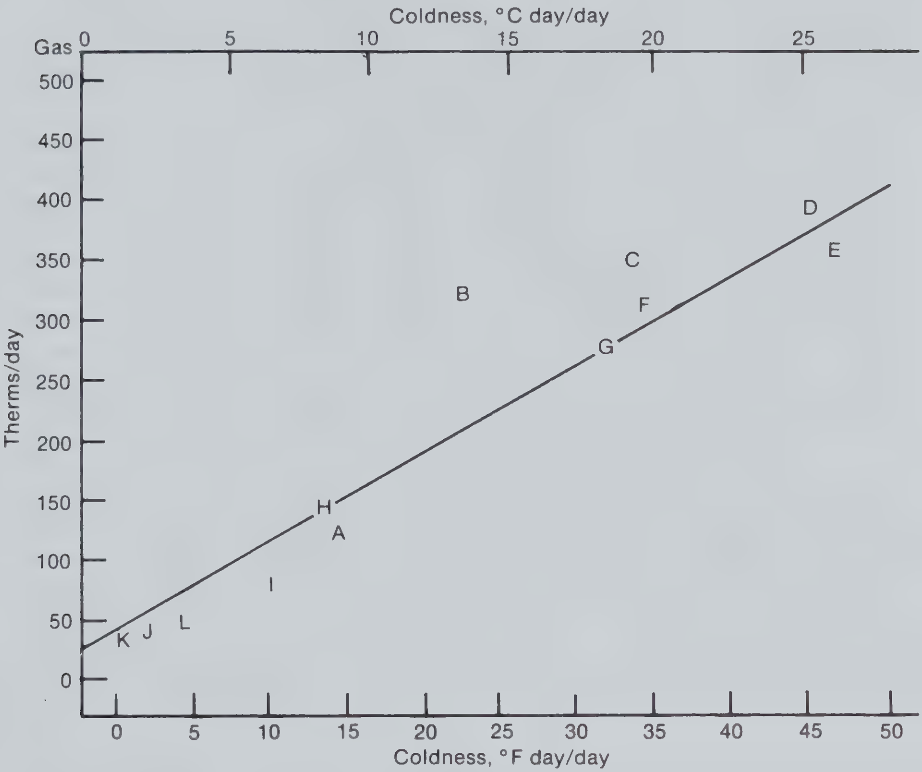


Figure 9. **Monthly energy use (letters) is plotted versus actual degree days with the line being the variable base degree day thermal model best fitting the monthly data** (Source: DeCicco, 1984)

fact that the regressed load coefficient was 1.7 times the value calculated from the plans. DeCicco could explain only part of the discrepancy. The analysis is complicated by the correlation between values for the load coefficient and the balance point temperature. Spot checks indicated that some of the apartments had open windows with high thermostat settings.

In general, the low amount of information and high potential for anomolous occurences in static master-meter data clearly limits the inferences possible from macrostatic methods. In DeCicco (1984), for example, new hot water boiler and controls for overheated common areas were installed. Although savings were undoubtedly achieved, the normalized annual consumption determined before and after the retrofits did not clearly show these savings. Other examples of how the macrostatic method leaves unanswered questions can be found in Hirst, White, and Goeltz (1983) and McKinstry and Busse (1983) which investigated audit accuracy.

A data-model mismatch is found in the DOE Class B procedure (Swisher et al., 1981; Shea et al., 1983). Here, macrodynamic zonal and end-use data were acquired but were generally time-integrated for application of a macrostatic thermal model. A measured dynamic load coefficient (dynamically corrected for infiltration) was used in a static model to calculate long-term loads. No weather or internal gains normalization were done. Buildings in the program were cross-compared by dividing directly measured seasonal totals by square footage and measured degree-days. Savings for passive solar components were obtained by subtracting auxiliary and other nonsolar gains from the thermal load computed by the static model. Thus, uncertainty in load calculation, opaque gains, uncertainties in internal gains calculations, etc., all introduce error in the component savings calculation. Clearly, more information in the dynamic data was available that was not used in the analysis, as will always be the case when dynamic data are matched with a static model.

Macrodynamic models hold much promise for use in industry, but have not been widely employed for several reasons. Both calculation and testing have not been well founded until recently (Subbarao, 1983; 1984; 1985; Subbarao, Mort, and Burch, 1985; Subbarao et al., 1985a&b), and dynamic data were not easily obtained until the advent of microcomputer-based data acquisition and control systems. Also, little need existed for such models in design until the advent of thermal mass storage and low-energy buildings.

As an example of a macrodynamic method, the dynamic, end-use, and zonal data for one residence were analyzed via a transfer function macrodynamic model (Subbarao, 1984). Eight system-level thermal parameters were extracted from one week of data. Figure 10 shows the fit of model to data and extrapolation beyond the period used for the regression. The extracted load coefficient and effective aperture area were compared to values expected from direct measurement and from plans. The regressed values were within probable error of expected values, although uncertainty in the dynamic parameters was large because the tests were noninterventive. One advantage of dynamic procedures like this is that

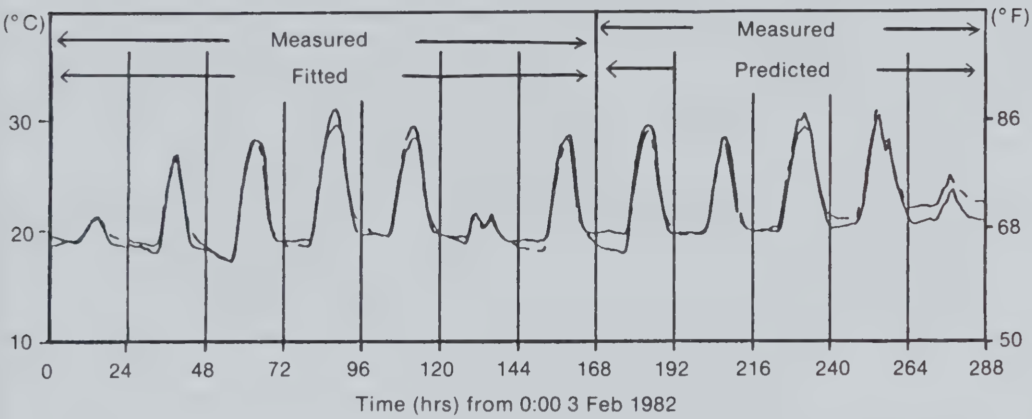


Figure 10. Temperature versus time in a residential sunspace, the solid line being measured and the dashed being the macrodynamic model predictions (Source: Subbarao, 1984)

monitoring need occur only over the short term, reducing costs and providing quick feedback.

Spatial mismatching occurs when a microdynamic simulation is matched with macrodynamic zonal and end-use data. Without further data, it is impossible to determine which of the hundreds of inputs are the source of the discrepancies and need to be adjusted to fit the data. Hill (1984), for example, obtained macrodynamic data from small commercial buildings, including measurement of zone temperatures, delivered thermal energy, and necessary inputs for weather and internal gains. He then modified the building description file based on agreement between predicted and measured air temperatures. Ground losses (i.e., floor area) were adjusted by 80% to fit the measured temperature decay after setback, although numerous other variables could be changed to cause the same result. Infiltration was set to zero. Internal mass was increased because the simulation over-responded to sharp changes. HVAC capacities were reduced based on measured energy delivery. Hill attempted numerous later modifications to change an apparent overreaction of the simulation to solar radiation but none were successful. The modified building files predicted loads 12% and 19% too low for the two cases.

In general, minimizing discrepancy between predicted and measured temperature only will generally lead to load discrepancies because of the problem of scale (Subbarao et al., 1985a). Arbitrarily selecting which inputs in a microdynamic simulation to vary in fitting a sequence of building response features is not an effective approach. A change of one input parameter to fit one feature (e.g., changing floor area for ground loss to fit temperature decay) will often be affected by later changes to fit other features (e.g., response to thermal inputs). It is preferable to use a model in which all the parameters can be uniquely and simultaneously determined through a building test.

CONCLUSIONS

Monitoring methods have common elements, consisting of a thermal model, a building test to determine model inputs, and model analyses. A monitoring method can be decomposed and understood by defining the choices for these key elements.

Major model classes are microdynamic, macrodynamic, and macrostatic, with only the latter two suited for monitoring applications. Like these models, testing data can be categorized on widely varying space and time levels. Useful methods must carefully match the time and space level of models with that of the data used.

In macrostatic methods, time-integrated data (such as utility bills for a season and degree-days between billings) are typically used to extract steady-state information (such as a load coefficient and balance point temperature) for a macrostatic model. In macrodynamic methods, dynamic data are used to determine the descriptive inputs for a macrodynamic building model. The data can be obtained in a few days if proper care is taken to eliminate some of the trade-off errors between parameters by manipulating internal gains and temperatures.

Macrostatic methods provide inexpensive means of assessing overall performance and verifying savings from major shell and equipment retrofits. In macrostatic analysis, detailed questions often elude explanation, such as verifying audit accuracy or separating effects from multiple measures. Macrodynamic methods can provide definitive answers on separate effects, including mass and solar-related issues, but have yet to be fully developed and exploited.

NOMENCLATURE

Symbols

C	thermal capacitance
F	forcing function driving a building
L	building load coefficient
P	thermal parameter describing a building
Q	thermal energy
R	thermal resistance or thermal response of a building
t	time
T	temperature

Subscripts

aux	auxiliary
bal	balance point
clamp	given or fixed
h	hour marker
in	interior
int	internal
out	outside
ref	reference
set	thermostat set point
store	thermal storage

ACKNOWLEDGMENTS

This work has been supported by the United States Department of Energy, Solar Buildings Technologies Division (under direction of Dave Pellish), within the Office of Solar Heat Technologies (under direction of Fred Morse).

REFERENCES

Arumi-Noe, F., and M. Wysocki, 1979. *DEROB III, The DEROB System*. Vols. 1-8, Austin, TX: Numerical Simulation Laboratory, University of Texas.

Balcomb, J.D., 1983. Thermal network reduction. *Proc. 1983 ASES Annual Solar Conf*. Boulder, CO: American Solar Energy Society.

Bickle, L., 1983. *SECS: Simplified Energy Calculation System*. Santa Fe, NM: Bickle and Associates.

Building Energy Associates, Inc., 1983. *The Identification and Development of Methods for the Extrapolation of Commercial Buildings Energy Performance*. Berkeley, CA: Lawrence Berkeley Laboratory.

Burch, J., 1984. *A Methodology for Testing of Mechanism Level Simulation of the Commercial Building Thermal Problem*. Unpublished. Available from J. Burch, Solar Energy Research Institute, 1617 Cole Blvd., Golden, CO 80401.

Burch, J., 1984. *A Methodology for Testing of Mechanism Level Simulation of the Commercial Building Thermal Problem.* Unpublished. Available from J. Burch, Solar Energy Research Institute, 1617 Cole Blvd., Golden, CO 80401.

Burns, P., P. Armstrong, and B. Winn, 1983. Passive solar/gas fired heating system characterization and development. *Proc. 8th National Passive Solar Conf.* Boulder, CO: American Solar Energy Society, p. 3.

Busch, J., and A. Meier, 1984. *Monitored Performance of New Low Energy Homes: Updated Results from the BECA-A Database.* LBL-18306. Berkeley, CA: Lawrence Berkeley Laboratory.

Deberg, P., 1979. *Use of General Models Having a Small Number of Parameters.* Preprint. Liege, Belgium.

DeCicco, J., 1984. *Analysis of Gas Consumption in Lumley Homes.* PU/CEES-WP-65, Princeton, NJ: Princeton University, Center for Energy and Environmental Studies.

Duffy, T., and H. Puri, 1985. Extrapolation of short-term measurements to long-term thermal performance of passive buildings. *Proc. 10th Passive Solar Conf.* Boulder, CO: American Solar Energy Society, p. 332.

Engineering Interface Limited, no date. *SUMAC: System for Utility Monitor, Analysis and Control.* Unpublished. Available from Engineering Interface Limited, Suite 200, 2 Sheppard Ave East, Willowdale, Ontario M2N5Y7.

Erbs, D., 1984. *Models and Applications for Weather Statistics Related to Building Heating and Cooling Loads.* Ph.D. Thesis, University of Wisconsin at Madison.

Eyre, D., 1983. *Case Study: The Monitoring and Analysis of House Thermal Performance.* SRC E-825-3-C-83. Saskatoon, Saskatchewan: Saskatchewan Research Council.

Fels, M., 1984. *The Princeton Scorekeeping Method: An Introduction.* PU/CEES Report 163. Princeton, NJ: Princeton University, Center for Energy and Environmental Studies.

Hamilton, B., 1984. *Yardsticks for Building Evaluation.* Presented at the Solar Federal Building Program meeting, 1983, Chicago. Unpublished. Available from the Memphremagog Group, 91 Henry Street, Burlington, VT 05401.

Hill, J., 1984. *A Case Study of Two Passive Solar Commercial Buildings, Vols. I, II.* DOE/CE/30742-17. Berkeley, CA: Lawrence Berkeley Laboratory.

Hirst, E., D. White, and R. Goeltz, 1983. *Comparison of Actual Electricity Savings with Audit Predictions in the BPA Residential Weatherization Pilot Program.* ORNL/CON-142, 124. Oak Ridge, TN: Oak Ridge National Laboratory.

Jansen, J., and R. Rasmussen, 1985. *Research and Development of a Diagnostic Procedure to Measure Changes in Thermal Integrity of Building Envelopes.* ORNL/Sub/84-47959/1. Oak Ridge, TN: Oak Ridge National Laboratory.

Kantrowitz, M., 1983. Occupancy effects and interactions in passive solar commercial buildings. *Proc. 8th National Passive Solar Conf.* Santa Fe, NM, Boulder, CO: ASES, p. 433.

Kroner, W., 1983. The impact of occupants on the performance of passive solar commercial buildings. *Proc. 8th National Passive Solar Conf.* Santa Fe, NM, Boulder, CO: ASES, p. 445.

Kusuda, T., 1985. Summary of recent activites on building energy simulation analysis in North America. *Proc. Building Energy Simulation Conf.* Golden, CO: Solar Energy Research Institute.

Kusuda, T., and T. Saitoh, 1980. *Simplified Heating and Cooling Energy Analysis Calculation for Residential Application.* NBSIR 80-1961. Washington, DC: National Bureau of Standards.

Kusuda, T., I. Sud, and T. Alareza, 1981. Comparison of DOE-2-generated residential design energy budgets with those calculated by the degree-day and bin method. *ASHRAE Transactions* 87.

Kusuda, T., T. Tschiya, and F. Powell, 1979. Prediction of indoor temperature by using equivalent thermal mass response factors. *Temperature: Its Measurement and Control.* H. Plumb, ed. Pittsburg, PA: Instrument Society of America.

Loftness, V., and R. Crenshaw, 1985. A survey of building performance indices. *Proc. ASHRAE/DOE/BTECC Thermal Envelope Conf.* Clearwater Beach, FL. Atlanta, GA: ASHRAE.

Madsen, J., 1983. *Transfer Functions for Heat Transfer Modeling.* M.S. Thesis, University of Wisconsin at Madison.

McKinstry, M., and P. Busse, 1983. *Evaluation of the BPA Standard Heat Loss Methodology Using Data from the BPA Pilot Weatherization Program.* Portland, OR: Office of Conservation, Bonneville Power Administration.

Muncey, R., J. Spencer, and C. Gupta, 1970. Method for thermal calculations using total building response factors. *NBS Building Science Series* 39, Washington, DC: National Bureau of Standards.

Oak Ridge National Laboratory, 1980. *RCS Model Audit.* ORNL/CON-106. Oak Ridge, TN: Oak Ridge National Laboratory.

Palmiter, L., and T. Wheeling, 1982. *SERIRES 1.0.* Golden, CO: Solar Energy Research Institute.

Rudoy, W., 1979. *Cooling and Heating Load Calculation Manual*, ASHRAE Special Publication GRP 158, Atlanta, GA: ASHRAE.

Shea, M., D. Mort, S. Mahajan, and C. Newcomb, 1983. *Documentation of Data Processing Procedures and Extension of Class B Data Analysis*. SERI/STR-254-2085. Golden, CO: Solar Energy Research Institute.

Sondereger, R.C., 1978. Diagnostic tests determining the thermal response of a house. *ASHRAE Transactions*, Vol. 84.

Subbarao, K., 1983. *Determining Passive Building Dynamics from Performance Data*. SERI/TR-274-1958, Golden, CO: Solar Energy Research Institute.

Subbarao, K., 1984. *BEVA (Building Element Vector Analysis) - A New Hour-by-Hour Building Energy Simulation with System Parameters as Inputs*. SERI/TR-254-2195, Golden, CO: Solar Energy Research Institute.

Subbarao, K., 1985. *Thermal Parameters for Single and Multizone Buildings and Their Determination from Performance Data*, SERI/TR-253-2617. Golden, CO: Solar Energy Research Institute.

Subbarao, K., J. Burch, C. Christensen, E. Hancock, and H. Jeon, 1985a. *Macrodynamic Theory and Short-Term Measurements for the Thermal Assessment of Buildings*. SERI/TR-253-2854. Golden, CO: Solar Energy Research Institute.

Subbarao, K., J. Burch, E. Hancock, and H. Jeon, 1985b. *Measurement of Building Thermal Capacitance*. SERI/TR-253-2855. Golden, CO: Solar Energy Research Institute.

Subbarao, K., D. Mort, and J. Burch, 1985. *Short-Term Measurements for the Determination of Envelope Retrofit Performance*. SERI/TP-253-2639. Golden, CO: Solar Energy Research Institute.

Sullivan, R., S. Nozaki, R. Johns, and S. Selkowitz, 1984. Commercial building energy performance analysis using multiple regression procedures. *Proc. ASHRAE Conf.* Atlanta, GA: ASHRAE.

Swisher, J., D. Frey, K. Harr, and M. Holtz, 1981. *Performance Monitoring of Passive Solar Residences at the Class B Level*. SERI/TP-254-1675. Golden, CO: Solar Energy Research Institute.

Ternoey, S., L. Bickle, C. Robbins, R. Busch, and K. McCord, 1985. *The Design of Energy-Responsive Commercial Buildings*. New York: John Wiley & Sons, Inc., 370 pp.

Train, K., J. Herriges, R. Windle, T. Alereza, 1984. *Combined Engineering/Statistical Approaches to Estimating End-Use Load Shapes*. EPRI-RP-2145-3. Palo Alto, CA: Electric Power Research Institute.

Wright, B., 1984. *Electric Demand Tape Analysis: Potential for Disaggregation of Energy End Use in Commercial Buildings.* Unpublished. Available from Wright Associates, 15 Blueberry Lane, Lexington, MA.

Xenergy, Inc., 1983. *Cost/Savings Algorithms used in XenCAP3.0.* Unpublished. Available from Xenergy, Inc., 60 Mall Rd., Burlington, MA 01803.

York, D.A., and E.F. Tucker, eds., 1980. *DOE-2 Reference Manual (Version 2.1).* Group WX-4, Program Support. Los Alamos, NM: Los Alamos Scientific Laboratory.

Passive Solar Journal, 3(2), 179-190 (1986)

Upholstery Textile Performance Following Exposure to Daylight

Sara Butler
Denise Guerin
Department of Home Economics
and Consumer Sciences
Miami University
Oxford, Ohio 45056

Abstract

This research investigated the effects of exposure to daylight on upholstery textiles. Eleven fabrics preferred by consumers were exposed to daylight in outdoor test cabinets for six months. Exposed and unexposed specimens were tested for tensile strength, elongation, abrasion resistance, and colorfastness. Statistical analysis indicated highly significant fabric/exposure interactive effects; significant losses in warp and filling strength, warp and filling elongation, and the resistance to abrasion in most of the exposed upholstery textiles tested. Color change was also found in the majority of exposed fabrics. Results indicate that careful selection of upholstery fabrics is required by energy-conscious consumers and designers.

INTRODUCTION

Today's passive solar designer has considerable research data available to determine technical design criteria for a building. However, although the design of the solar building envelope has reached a sophisticated level, the design of the interior space and specification for interior materials is only now being recognized as an area needing further study.

Designers of passive solar buildings are becoming aware that textiles, woods, and plastic products are subject to color change and degradation when exposed to direct or indirect daylight. One of these materials, textiles, represents a difficult problem for users of direct or indirect gain in residences as well as commercial daylighting applications. Because many textiles are subject to a process of color change and deterioration when exposed to daylight, research focusing on the performance of interior textiles following exposure to daylight is critical. This research project focused particularly on characteristics of upholstery textiles after exposure to daylight.

Deterioration in upholstery textiles results from exposure to ultraviolet, visible, or infrared radiation. Although glass absorbs most ultraviolet light, even the small amount passing through can damage textiles. Glass allows most of the visible radiation to pass through where it may cause various types of textile deterioration directly or as reradiated infrared radiation. Most fabrics are subject to damage from light, but the rate and amount of deterioration vary according to the textile's fiber content, yarn and fabric construction, finish, and dye methods. When daylight with the inherent properties of ultraviolet, visible, or infrared radiation is added to these factors, chemical and physical reactions may be accelerated.

Several previous studies have investigated the effects of exposure to light on various textiles. Strait (1970) found decreased breaking strength in flame retardant fabrics after carbon-arc exposure in the laboratory. Using yarns, Wall and Frank (1971) found losses in breaking extension and energy to break using both xenon-arc and outdoor exposure tests. Mee (1975), using outdoor exposure behind glass and in a laboratory fadeometer, found that the strength of nylon and nylon blend drapery fabrics was significantly affected.

Crews and Stevens (1974) exposed a phenolic fabric behind glass and found that the strength decreased as the length of exposure increased. None of these studies used upholstery textiles as test specimens, however. In a study of upholstery textiles (Harabin, Ostrander, and Stout, 1973) five universities investigated fabric performance through laboratory tests and actual use as well as consumer satisfaction. Laboratory exposure to light caused notable color change in all six fabrics tested. Five fabrics also lost strength with light exposure.

The study undertaken here is unique in that outdoor exposure cabinets were used, and upholstery fabrics available in the retail market were selected as test specimens. Outdoor exposure test cabinets were selected as the appropriate equipment to simulate, as closely as possible, actual conditions of exposure in a passive solar building. The cabinets allowed the researchers to use double glazing, air vents to allow heat to flow through natural convection, and exposure to humidity. The glass used in the exposure cabinets was a double glazed standard window of 3/16 in. tempered glass with a transmission value of 72%. The specimens were exposed to daylight for a period of six months, the average Ohio heating season. Exposure began in October, approximating the end of fall shading of glazing and ended in April, the beginning of spring shading. The other factor unique to this research was the use, for test specimens, of fabrics preferred by consumers. This study was seen as a preliminary investigation of how commonly used upholstery fabrics perform in light conditions similar to those found in passive solar buildings.

PROCEDURE

Sample Selection

A style survey conducted by *Home Furnishings Daily* (1979) was used as a guide in selecting the sample of 11 upholstery fabrics. In the survey, 82 retailers were asked to rank consumer preferences regarding colors, fabrics and fibers of upholstered furniture. At that time, tan, brown, rust, and blue were seen as the most popular colors. The most desirable fabrics were velvets, cotton prints, and jacquards, respectively. Olefin, cotton, and nylon were seen as the fibers demanded the most by consumers. Although no precise formula for sample selection in relation to the *Home Furnishings Daily* survey was established, a similar balance of the three characteristics was maintained when choosing the sample fabrics.

Exposure Conditions

To achieve the objective of examining the effects of daylight, two sets of fabrics were tested: those exposed to daylight and those unexposed. Procedures for light exposure were similar to those specified by the American Association of Textile Chemists and Colorists (AATCC) "Colorfastness to Light through Glass: Daylight," Method 16C-1977 (AATCC, 1982). Because AATCC-specified cabinets were not available in small quantities, two cabinets were custom made. The cabinets were placed in an unshaded, secured, outdoor area and faced due south with 45°-sloped, double glazing. Double glazing with transmission of 72% was used in order to simulate windows in a passive solar building. The 11 test fabrics were precut and placed in the cabinets on October 15, 1980, and remained there until April 15, 1981. This six-month span was considered to cover the Columbus, Ohio, heating season at 40° north latitude.

Test Conditions

Descriptive data were collected on all 11 fabrics. In addition, four exposed and four unexposed specimens for each sample fabric were tested for tensile strength, elongation, abrasion resistance, and colorfastness. All specimens were preconditioned in a laboratory oven and then conditioned in an environmental chamber allowing testing at consistent levels of temperature and humidity--factors that can affect textile test results. The American Society of Testing Materials (ASTM D-1682) cutstrip method was used to test tensile strength and elongation on a constant rate of traverse Scott Tester. In this method, specimens are subjected to pulling forces until failure, at which point the force required to rupture the specimen measured in kilograms is recorded. Elongation, the stretch of the fabric at the point of rupture, is measured in centimeters and graphed simultaneously. Both warp (lengthwise) and filling (crosswise) specimens were tested for strength and elongation. Abrasion resistance was evaluated using the AATCC impeller tumbler method. Specimens were weighed, rotated in a chamber lined with an abrasive material, then reweighed. The percentage of weight loss was then calculated. Color change was evaluated by a panel of three judges using the International Geometric Gray Scale (AATCC Evaluation Procedure 1). The exposed and unexposed specimens were compared to gray chips, and a numerical value was assigned to each fabric indicating the degree of color change. The above results were analyzed using two-way analysis of variance and t-tests.

RESULTS

Descriptions of the fabric samples are provided in Table 1. The 11 fabrics represent a range of weights, thicknesses, and thread counts. Results of the tests are in Tables 2 and 3.

Two-way analysis of variance was used to examine overall differences among fabrics, unexposed/exposed differences, and interactive effects for the four laboratory tests. Overall differences were found between exposed and unexposed fabrics at the 0.001 level on warp strength, filling strength, warp elongation, filling elongation, and abrasion. All fabric/exposure interactive effects were significant at the 0.001 level, indicating the importance of the fabric/exposure combination.

Follow-up statistical tests provided more detailed information (Table 2). Nine of the 11 fabrics were found to have significant warp (lengthwise) strength loss after exposure to light. Of those that lost strength, fabrics 1, 4, and 11 were cottons; fabrics 3 and 7 were nylons; and fabrics 6 and 8 were olefins. Fabrics 9 and 10, acrylic and rayon velvets respectively, lost no significant strength after exposure. Filling (crosswise) results were similar. Again, fabrics 1, 4, and 11 (cottons), fabrics 3 and 7 (nylons), and fabrics 6 and 8 (olefins), lost very significant amounts of strength. Fabrics 9 and 10 (acrylic and rayon velvets) again performed well.

Significant decreases in warp elongation after exposure were found for fabrics 3 and 7 (nylons), fabrics 6 and 8 (olefins), and fabric 4 (cotton chintz). Decreases were significant in filling elongation for fabric 6 (olefin), fabric 7 (nylon), and fabric 9 (acrylic-faced velvet). The significant increase in filling elongation for fabric 5 (rayon/cotton) is somewhat unusual but confirms the results of Harabin et al. (1973).

Table 1. Fabric Descriptions

Fabric Number and Common Name	Weave	Fiber Content	Weight $(kg/m^2)^a$	Thickness $(cm)^b$	Threads/$cm^{b,c}$
1. Cotton	Dobby doublecloth	100% cotton	0.30	0.18	W = 12 F = 12 (each part)
2. Blended tapestry	Jacquard (tapestry-like)	65% rayon, 23% polyester, 12% acetate	0.57	0.26	W = 10 F = 12
3. Nylon solid	Basket	100% nylon	0.44	0.24	W = 12 F = 12
4. Cotton chintz	Sateen	100% cotton	0.20	0.06	W = 38 F = 22
5. Blended dobby	Dobby	63% rayon, 37% cotton	0.37	0.15	W = 38 F = 18
6. Chain-stitch olefin	Chain stitch	100% olefin	0.53	0.30	No warp F = 3
7. Nylon print	Plain	100% nylon	0.51	0.25	W = 3 F = 3
8. Olefin plaid	Twill	100% olefin	0.68	0.38	W = 3 F = 5
9. Acrylic-faced velvet	Velvet	100% acrylic face, 100% cotton back	0.57	0.18	W = 30 F = 10
10. Rayon-faced velvet	Velvet	100% rayon face, 100% cotton back	0.63	0.21	W = 30 F = 22
11. Cotton velvet	Velvet	100% cotton	0.47	0.23	W = 17 F = 14

[a] 1 kg = 2.2 lb; 1 m^2 = 1.20 yd^2

[b] 1 cm = 0.3937 in.

[c] W = warp (lengthwise), F = filling (crosswise)

Table 2. Strength, Elongation, and Abrasion Results[a]

Fabric	Warp Strength kg[b]		Filling Strength kg[b]		Warp Elongation cm[c]		Filling Elongation cm[c]		Abrasion (% wt loss)	
	Unexposed	Exposed	Unexposed	Exposed	Unexposed	Exposed	Unexposed	Exposed	Unexposed	Exposed
1. Cotton double-cloth	164.80	50.60[d]	147.14	44.00[d]	3.00	3.05	1.65	1.27	3.93	16.18[d]
2. Blended tapestry	288.86	239.36[d]	341.73	176.55[d]	4.06	5.21	2.67	2.49	13.3	12.08
3. Nylon solid	237.34	36.85[d]	501.89	242.55[d]	7.11	2.67[d]	4.90	4.19	5.15	9.78[d]
4. Cotton chintz	152.64	30.80[d]	43.19	1.23[d]	1.02	0.51[d]	2.16	0.89	6.7	58.3[d]
5. Blended dobby	194.70	142.12[d]	199.28	140.54	2.24	1.98	2.16	3.00[d]	9.08	14.6[d]
6. Chain-stitch	111.10	33.00[d]	77.55	9.90[d]	9.02	0.46[d]	10.11	0.64[d]	16.8	58.98[d]
7. Nylon print	84.70	2.20[d]	262.02	44.84[d]	2.87	0.97[d]	4.90	2.24[d]	11.23	72.35[d]
8. Olefin plaid	108.90	25.04[d]	208.74	160.60[d]	4.70	1.27[d]	4.06	3.94	61.8	52.1
9. Acrylic-faced velvet	147.14	125.40	121.29	126.79	1.91	2.24	2.74	2.29[d]	11.55	41.13[d]
10. Rayon-faced velvet	97.09	90.75	195.25	196.79	2.49	2.54	1.60	1.73	18.55	32.60
11. Cotton velvet	108.90	91.30[d]	95.70	74.25[d]	2.29	1.98	1.27	1.09	10.2	39.28[d]

[a] N = 4 (each test is run on 4 specimens and a mean of those results are used).

[b] 1 kg = 2.2 lb

[c] 1 cm = 0.3937 in.

[d] $p \leq 0.05$ (p is the level of significance, meaning the probability that the findings are due to chance and not to exposure. While important, the means may not reflect the statistical significance of the change.)

Table 3. Color Change Results

Fabric	Gray Scale Rating[a]
1. Cotton doublecloth	1.95
2. Blended tapestry	3.40
3. Nylon solid	1.8
4. Cotton chintz	3.06
5. Blended dobby	2.67
6. Chain-stitch olefin	5.0
7. Nylon print	2.65
8. Olefin plaid	4.28
9. Acrylic-faced velvet	4.5
10. Rayon-faced velvet	2.8
11. Cotton velvet	1.4

[a] 1-5 scale, 5 indicating no color change; results are the means of 4 specimens.

Abrasion results, measured using the weight loss method, indicated that all but fabric 2 (rayon blend), fabric 8 (olefin), and fabric 10 (rayon) experienced a significant increase in the percentage of weight loss after daylight exposure. Fabric 4 (cotton) and fabric 7 (nylon) experienced the largest percentage of weight loss whereas fabric 3 (nylon) and fabric 5 (rayon/cotton) were affected less.

Color change results are presented in Table 3. Gray Scale evaluations were made for each hue in the specimen by each of the three judges, then averaged. The Gray Scale rating is based on a 1 to 5 scale. A lower number indicates a greater color change; a 5 rating represents no color change. Only fabric 6, an olefin, had no color change. In several fabrics, colors faded unevenly, with little loss for some colors of a plaid or print, and noticeable loss in other colors. Color change was unrelated to the color of a fabric (e.g., tans/browns or blues). Both olefins performed well, as did the acrylic-faced velvet. All other fabrics were below 4, indicating a visible color change.

DISCUSSION

The objective of this study was to examine the effects of exposure to daylight on fabrics preferred by consumers rather than on laboratory fabrics. The resulting variability of color and fabric structure made some of the testing and analysis somewhat difficult, however. In addition, it is impossible to measure the effects of two factors occurring at the same time, which would likely happen in an actual use situation (e.g., stress and abrasion). Laboratory testing does allow for increased control of variables, however, so that direct comparisons between fabrics can be made. With these considerations in mind, the results of this study indicate that none of the fabrics used performed exceptionally well in every category following daylight exposure.

Most fabrics lost significant amounts of strength in both the lengthwise (warp) and crosswise (filling) directions. The losses in strength found were consistent with the research previously cited (Strait, 1970; Wall and Frank, 1971; Mee, 1975; Crews and Stevens, 1974). In a practical sense, strength loss may result in ruptured seams on upholstered pieces and, in extreme cases, tears or rips in the fabric itself. The relative differences in the fabrics must be considered when evaluating the results. For example, although both the blended tapestry and the nylon print lost statistically significant amounts of strength following exposure, the exposed nylon print was able to resist only about 2 kg (4 lb) of stress before failure, while the exposed blended tapestry withstood almost 240 kg (528 lb) before it ruptured. Therefore, selections must be made based on the initial strength of the fabric coupled with the effects of daylight.

Elongation results indicate of the amount of stretch or give in a fabric. Decreased elongation will result in a stiffer or more rigid fabric. Only two fabrics, the chain-stitched olefin (fabric 6) and the nylon print (fabric 7), experienced significantly decreased elongation in both the lengthwise and crosswise directions. The construction of an upholstered piece would greatly affect the need for elongation in a fabric. If the fabric was pulled tightly over cushions and frame, some give in the fabric would be critical to accommodate the stress incurred during use. In a looser construction, however, seat and back cushions could absorb the stress, thus requiring less elongation in the covering material. As in the strength results, elongation potential for each fabric must be evaluated in relation to the other fabrics. Certain fabrics had greater elongation overall than did others. Elongation varied considerably in the warp and filling directions as well.

The ability of a fabric to resist abrasion is a critical factor in evaluating upholstery. Eight of the 11 fabrics tested lost a significant percentage of weight following exposure to daylight. Abrasion is a variable that cannot be alleviated by construction since all upholstered furniture is subjected to abrasive forces in use. In addition, abrasion occurs unevenly in that seats and seatbacks abrade more than furniture backs and sides. Appearance may be an important factor to consider in this instance, and again, the relative differences between fabrics must be noted. While the exposed nylon solid sample lost only 10% of its weight due to abrasion after exposure, the nylon print lost more than 70%. The anticipated degree of use of an item in addition to the level of daylight exposure should be considered when making furniture selections.

For the most part, the color change that occurred in the fabrics would affect appearance. As with abrasion, color change would likely occur inconsistently, depending on the placement of a piece of furniture with respect to the light source. In certain applications, appearance may outweigh durability considerations. The chain-stitch olefin, the olefin plaid and the acrylic-faced velvet all experienced relatively little color change, making them prime candidates when appearance is critical.

CONCLUSION

When viewed in relation to the *Home Furnishings Daily* style survey, the results display an interesting pattern. The velvets, seen as the preferred fabric by the retailers surveyed, performed reasonably well as a group. The rayon-faced velvet, in fact, had no significant losses of either strength or abrasion resistance. The cotton chinz, also rated as a popular fabric, had very significant losses of strength and abrasion resistance. Most interesting is the comparison of fiber contents, however. The retailers surveyed indicated that consumers preferred olefin, cotton, and nylon, in that order. Both olefins tested lost significant amounts of strength when exposed to light and experienced some decrease in elongation. Similarly, the nylons tested performed poorly in all three areas. The nylon fabrics also faded noticeably, whereas the olefin fabrics received relatively high colorfastness ratings. The cottons all experienced losses in strength and resistance to abrasion but performed better in the elongation tests. All of the cotton fabrics lost color to some extent. These comparisons indicate that, for the most part, what the consumer prefers may not be the best choice for homes receiving a large amount of daylight if durability is an important factor.

Correlation between exposure in an outdoor cabinet and exposure in a residential or commercial situation is difficult. Most consumers, however, would expect upholstered furniture to be durable over a period of years. Although the exposure conditions of this study were probably more severe, the time span was only six months. The implication is that consumer needs in relation to upholstered items must be carefully evaluated. For example, the chain-stitch olefin specimen performed poorly on the durability tests but lost no color. It may be an acceptable choice if durability is of little consequence but colorfastness is extremely important (a seldom used decorative chair in a greenhouse, for example). Conversely, if durability is of primary importance, fabric 10, the rayon-faced velvet, may prove to be a good choice because it lost no strength, elongation, or resistance to abrasion. Color change could then be mediated by color selection and furniture placement.

Follow-up research must be conducted to further isolate fibers and fabrics most affected by daylight conditions similar to those found in passive solar structures. Results of such research must be made available to consumers and interior designers so that appropriate selections can be made in relation to consumer needs. A more accurate, quantitative color change evaluation would be achieved with a color spectrometer and should be considered for future studies. Additional research should also be conducted to identify the relationship of glass, with different levels of daylight transmission, to textile performance in an effort to gain better control over the design of solar interior environments.

ACKNOWLEDGMENTS

We gratefully acknowledge support by the Ohio Inter-University Energy Research Council, the Miami University Faculty Research Committee, and the Department of Home Economics and Consumer Sciences.

REFERENCES

AATCC, 1982. *Technical Manual of the American Association of Textile Chemists and Colorists, 1981/82.* Vol. 57. Research Triangle Park, NC: AATCC.

Crews, P., and H. Stevens, 1974. Fire resistance, strength and spectrum of phenolic fabric exposed to weather and sunlight behind glass. *Home Economics Research Journal* 3:14-23.

Home Furnishings Daily, 1979 (July). Style survey. Vol. 9, p. 8.

Harabin, D., E.R. Ostrander, and E.E. Stout, 1973. *Properties of Textile Upholstery Fabrics and Their Importance to Consumer Satisfaction.* Cornell University Agricultural Experiment Station Bulletin 1032, pp. 1-55.

Mee, G., 1975. *Effects of Light and Weathering on Strength and Flaming Characteristics of Drapery Fabrics.* Master's Thesis, Florida State University.

Strait, D.A., 1970. *The Effect of Carbon Arc Light on Selected Fabrics Treated with Three Flame Retardant Finishes.* Master's Thesis, Louisiana State University.

Wall, M.J., and G.C. Frank, 1971. A study of the spectral distribution of sun-sky and xenon arc radiation in relation to degradation of some textile yarns. *Textile Research Journal* 41:32-37.

Passive Solar Journal, 3(2), 191-206 (1986)

Daylighting Data Compendium

Claude L. Robbins
Kerri C. Hunter
Solar Energy Research Institute
1617 Cole Boulevard
Golden, Colorado 80401

Abstract

A radiation data base for use in analyzing the performance characteristics of passive solar thermal systems has existed for many years. Such a data base for designing and analyzing daylighting systems has not previously existed on a city-by-city basis.

This paper describes the end result of a multiyear research effort at SERI to develop a mathematical model to describe the daylight resource in various cities and to publish the resulting data in a format useful to architects, engineers, and lighting designers.

INTRODUCTION

To a building designer, daylighting is an energy-efficient and cost-effective alternative to electric lighting in buildings. To be successful, the daylighting option should be considered early in the design process so it can be integrated with a variety of related design concerns. Local daylight resource data are required for computations of the performance of daylighting and lighting control systems by standard analytic methods.

This paper describes a compendium of daylight data, which was designed specifically for use with existing analysis methods to define the lighting and energy performance characteristics of daylighting systems. Three types of data--daylight availability, sunlight availability, and daylighting utilization factors--for selected cities within a single geographic region of the country are included in each volume of the compendium. Data have been generated for a total of 244 cities in the TMY/ETMY network. Data for 75 cities are found in *Daylighting Design and Analysis* (Robbins, 1986).

DAYLIGHT AVAILABILITY

Daylight availability data represent the instantaneously available natural illumination striking surfaces of different orientation. These data are used in several well-known techniques (daylight factor method, lumen input method, flux transfer method) for calculating daylight's contribution to interior illuminance (amount of light per unit area).

Tables 1 and 2 for Denver, Colorado, are samples of the full data set. They give the instantaneously available natural illumination that will strike surfaces having various orientations. The data format follows that for solar heat gain factors in the ASHRAE handbook (ASHRAE, 1985). All values are for illuminance, the luminous flux per unit area at a point on a surface, and are in units of lux, or lumens per square meter. This is a metric measure; the corresponding English unit of illuminance is footcandles, or lumens per square foot. Illuminance in lux is converted to illuminance in footcandles by dividing by 10.76.

Table 1. Daylight Availability for Denver, Colorado

A	B	C	D	E	F	G	H	I	J	K	L	M	
	TIME	DIRECT NORMAL CLEAR (LUX)	NORTH VERTICAL GLOBAL CLEAR (LUX)	NORTHEAST VERTICAL GLOBAL CLEAR (LUX)	EAST VERTICAL GLOBAL CLEAR (LUX)	SOUTHEAST VERTICAL GLOBAL CLEAR (LUX)	SOUTH VERTICAL GLOBAL CLEAR (LUX)	VERTICAL GLOBAL OVERCAST (LUX)	HORIZONTAL GLOBAL CLEAR (LUX)	HORIZONTAL DIFFUSE CLEAR (LUX)	HORIZONTAL GLOBAL OVERCAST (LUX)	TIME	
JAN 21	8	46110	2770	12330	44700	52920	31760	1890	10250	3530	5060	16	JAN
	9	72910	5130	6470	59630	82570	61210	3680	27130	5590	8000	15	
	10	83130	6530	8090	51120	88280	78980	5070	40490	6370	10240	14	
	11	87480	7020	8640	32850	82350	89310	5990	48940	6700	11990	13	
	12	88730	6760	8340	10190	69030	93120	6320	51820	6800	12650	12	
	13	87480	7020	7450	9150	49870	89310	5990	48940	6700	11980	11	
	14	83130	6530	6040	7450	28390	78980	5070	40490	6370	10240	10	
	15	72910	5130	4220	5170	7610	61210	3680	27130	5590	8000	9	
	16	46110	2770	2240	2510	3090	31760	1890	10250	3530	5060	8	
FEB 21	7	23080	1610	13570	27160	25310	9640	1010	3470	1710	3050	17	FEB
	8	69730	5100	27030	70500	76150	40680	3240	23200	5160	7340	16	
	9	85490	7330	16060	73870	93140	63780	5130	41810	6330	10350	15	
	10	92310	8660	10610	60350	94290	79840	6690	56230	6840	13430	14	
	11	95400	9130	10950	38500	85560	89650	7740	65320	7070	15710	13	
	12	96310	8760	10440	12580	69990	93480	8110	68420	7130	16530	12	
	13	95400	9130	9400	11310	48500	89650	7740	65320	7070	15710	11	
	14	92310	8660	7850	9400	24890	79840	6690	56230	6840	13430	10	
	15	85490	7330	6160	7010	8830	63780	5130	41810	6330	10350	9	
	16	69730	5100	4170	4350	5450	40680	3240	23200	5160	7340	8	
	17	23080	1610	1440	1390	1590	9640	1010	3470	1710	3050	7	
MAR 21	7	53690	4430	38180	62180	52080	14420	2530	15510	4820	6230	17	MAR
	8	77100	7650	41180	81460	79150	35530	4750	36560	6930	9690	16	
	9	86680	9600	28350	78290	88780	54290	6800	54910	7790	13680	15	
	10	91330	10680	12920	63550	87880	68910	8550	69010	8200	17490	14	
	11	93550	11090	13030	40970	78260	78040	9750	77880	8400	20000	13	
	12	94220	10580	12290	14510	62360	82000	10200	80910	8460	20860	12	
	13	93550	11090	11070	13010	40440	78040	9750	77880	8400	20000	11	
	14	91330	10680	9400	10920	16880	68910	8550	69010	8200	17490	10	
	15	86680	9600	8120	8650	10640	54290	6800	54910	7790	13680	9	
	16	77100	7650	6170	6090	7450	35530	4750	36560	6930	9690	8	
	17	53690	4430	3470	3220	3800	14420	2530	15510	4820	6230	7	
APR 21	6	31060	8580	31660	38620	23620	2950	1700	7750	3690	4670	18	APR
	7	66360	7580	56690	77240	57210	7960	4030	29480	7880	8540	17	
	8	80600	10400	54660	86090	74100	24840	6310	50430	9580	12630	16	
	9	87550	12140	41270	80250	80170	41090	8500	68430	10400	17390	15	
	10	91240	13100	22550	65310	78430	54680	10450	82230	10840	21320	14	
	11	93100	13400	15320	43280	69280	64080	12040	90900	11080	24160	13	
	12	93660	12780	14330	16440	53240	68650	12750	93850	11130	25480	12	
	13	93100	13400	12920	14660	30750	64080	12040	90900	11080	24160	11	
	14	91240	13100	11560	12540	14660	54680	10450	82230	10840	21320	10	
	15	87550	12140	10330	10320	12130	41090	8500	68430	10400	17390	9	
	16	80600	10400	8290	7840	9070	24840	6310	50430	9580	12630	8	
	17	66360	7580	5600	5100	5620	7960	4030	29480	7880	8540	7	
	18	31060	8580	2590	2270	2420	2950	1700	7750	3690	4670	6	
MAY 21	5	2260	2540	6250	5830	2210	1070	450	430	350	1460	19	MAY
	6	46710	19270	50180	54970	30380	4910	2790	17580	7280	6650	18	
	7	69180	17920	64980	79200	53130	9100	5030	38950	10790	10170	17	
	8	79760	12340	61880	84620	66230	15590	7320	58800	12430	14810	16	
	9	85410	13870	48970	78040	70380	29880	9560	75730	13320	19610	15	
	10	88560	14750	31400	63550	67870	41880	11740	88680	13810	23630	14	
	11	90180	14940	16730	43120	59710	50810	14020	96810	14060	28120	13	
	12	90680	14370	15530	17440	43920	55610	15360	99580	14140	31380	12	
	13	90180	14940	14140	15450	22420	50810	14020	96810	14060	28120	11	
	14	88560	14750	13250	13560	15300	41880	11740	88680	13810	23630	10	
	15	85410	13870	11860	11460	12890	29880	9560	75730	13320	19610	9	
	16	79760	12340	9730	9080	9920	15590	7320	58800	12430	14810	8	
	17	69180	17920	7360	6800	6910	9100	5030	38950	10790	10170	7	
	18	46710	19270	4470	3800	3870	4910	2790	17580	7280	6650	6	
	19	2260	2540	1010	1250	1230	1070	450	430	350	1460	5	
JUN 21	5	9200	7230	14700	13370	5340	1770	950	2320	1650	2900	19	JUN
	6	49240	23300	54440	57440	30340	5630	3190	21390	8860	7270	18	
	7	68280	22090	66700	77930	50170	9680	5400	42120	12280	10850	17	
	8	77760	14280	63720	82550	62170	13120	7690	61190	13980	15610	16	
	9	82980	14640	51280	75930	65600	25390	9930	77430	14920	20350	15	
	10	85950	15440	34210	61400	62240	36250	12240	89830	15460	24520	14	
	11	87490	15600	17150	41220	53630	43590	14950	97600	15730	30350	13	
	12	87970	15270	15990	17550	37820	47490	16760	100250	15820	35360	12	
	13	87490	15600	14890	15740	18880	43590	14950	97600	15730	30350	11	
	14	85950	15440	14090	14140	15550	36250	12240	89830	15460	24520	10	
	15	82980	14640	12550	12130	13230	25390	9930	77430	14920	20350	9	
	16	77760	14280	10350	9800	10280	13120	7690	61190	13980	15610	8	
	17	68280	22090	8110	7280	7430	9680	5400	42120	12280	10850	7	
	18	49240	23300	5290	4450	4470	5630	3190	21390	8860	7270	6	
	19	9200	7230	1740	1750	1710	1770	950	2320	1650	2900	5	
				NORTHWEST VERTICAL (LUX)	WEST VERTICAL (LUX)	SOUTHWEST VERTICAL (LUX)							

(continued)

Table 1. Daylight Availability for Denver, Colorado (Direct Normal and Global) (concluded)

A	B TIME	C DIRECT NORMAL CLEAR (LUX)	D NORTH VERTICAL GLCBAL CLEAR (LUX)	E NORTHEAST VERTICAL GLOBAL CLEAR (LUX)	F EAST VERTICAL GLOBAL CLEAR (LUX)	G SOUTHEAST VERTICAL GLOBAL CLEAR (LUX)	H SOUTH VERTICAL GLOBAL CLEAR (LUX)	I VERTICAL GLOBAL OVERCAST (LUX)	J HORIZONTAL GLOBAL CLEAR (LUX)	K HORIZONTAL DIFFUSE CLEAR (LUX)	L HORIZONTAL GLOBAL OVERCAST (LUX)	M TIME	
JUL 21	5	2260	2710	6440	5970	2370	1140	510	540	450	1650	19	JUL
	6	42380	18470	46710	50900	23180	4980	2840	17950	8430	6730	18	
	7	63410	17670	61000	73810	49500	9070	5070	38870	12610	10260	17	
	8	73500	12250	58570	79290	61950	14790	7370	57580	14620	14910	16	
	9	78940	13690	46750	73430	65980	28110	9610	73620	15700	19700	15	
	10	81990	14500	30480	60110	63770	39350	11800	85840	16310	23740	14	
	11	83570	14640	16430	41190	56400	47840	14130	93500	16620	28360	13	
	12	84050	14040	15190	17110	41840	52540	15510	96100	16720	31800	12	
	13	83570	14640	13800	15110	21360	47840	14130	93500	16620	28360	11	
	14	81990	14500	12990	13270	15000	39350	11800	85840	16310	23740	10	
	15	78940	13690	11670	11240	12870	28110	9610	73620	15700	19700	9	
	16	73500	12250	9630	8960	9780	14790	7370	57580	14620	14910	8	
	17	63410	17670	7370	6590	6890	9070	5070	38870	12610	10260	7	
	18	42380	18470	4550	3850	3920	4980	2840	17950	8430	6730	6	
	19	2260	2710	1070	1280	1280	1140	510	540	450	1650	5	
AUG 21	6	25620	7950	27490	33360	20450	3020	1750	8020	4570	4770	18	AUG
	7	58000	7620	51350	69310	51380	7640	4070	29430	10360	8600	17	
	8	71770	10340	50500	78470	67450	22990	6350	49430	12820	12720	16	
	9	78640	11970	38780	73820	73470	37910	8550	66400	14040	17490	15	
	10	82310	12830	21910	60620	72280	50490	10500	79340	14700	21420	14	
	11	84160	13080	15000	40690	64230	59310	12110	87440	15030	24290	13	
	12	84730	12420	13980	16090	49630	63710	12840	90200	15130	25650	12	
	13	84160	13080	12580	14310	28870	59310	12110	87440	15030	24290	11	
	14	82310	12830	11280	12250	14370	50490	10500	79340	14700	21420	10	
	15	78640	11970	10140	10120	11920	37910	8550	66400	14040	17490	9	
	16	71770	10340	8210	7750	8960	22990	6350	49430	12820	12720	8	
	17	58000	7620	5620	5100	5620	7640	4070	29430	10360	8600	7	
	18	25620	7950	2650	2310	2460	3020	1750	8020	4570	4770	6	
SEP 21	6	280	70	1220	3860	1190	70	60	40	40	200	18	SEP
	7	46550	4500	34460	55400	46280	13040	2590	15650	6180	6320	17	
	8	69280	7850	38450	74700	72320	32620	4800	36150	9210	9780	16	
	9	78930	9520	27190	72710	82010	50220	6860	53750	10490	13810	15	
	10	83670	10520	12770	59590	81700	64040	8610	67200	11120	17630	14	
	11	85960	10880	12830	38820	73040	72690	9830	75640	11420	20140	13	
	12	86650	10350	12060	14280	58400	76510	10280	78520	11510	21010	12	
	13	85960	10880	10850	12790	37960	72690	9830	75640	11420	20140	11	
	14	83670	10520	9220	10740	16070	64040	8610	67200	11120	17630	10	
	15	78930	9520	8020	8510	10520	50220	6860	53750	10490	13810	9	
	16	69280	7850	6150	6080	7420	32620	4800	36150	9210	9780	8	
	17	46550	4500	3510	3280	3840	13040	2590	15650	6180	6320	7	
	18	280	70	830	670	830	70	60	40	40	200	6	
OCT 21	7	16430	1490	10290	20620	19260	7540	960	2880	1690	2910	17	OCT
	8	60280	4900	23930	62150	67330	36410	3190	21520	6190	7270	16	
	9	76050	7030	14740	66740	84460	58270	5070	39030	7810	10250	15	
	10	82950	8270	10210	55300	86300	73370	6620	52520	8520	13290	14	
	11	86090	8690	10510	35650	78720	82560	7670	61000	8850	15570	13	
	12	87020	8310	9980	12120	64700	86180	8040	63890	8940	16380	12	
	13	86090	8690	8960	10870	45070	82560	7670	61000	8850	15570	11	
	14	82950	8270	7480	9020	23500	73370	6620	52520	8520	13290	10	
	15	76050	7030	5870	6730	8540	58270	5070	39030	7810	10250	9	
	16	60280	4900	3990	4170	5250	36410	3190	21520	6190	7270	8	
	17	16430	1490	1360	1300	1490	7540	960	2880	1690	2910	7	
NOV 21	8	41590	2680	11310	40840	48440	29210	1850	9630	3680	4990	16	NOV
	9	68090	4990	6320	56200	77870	57900	3640	25950	6030	7950	15	
	10	78310	6360	7910	48610	83900	75200	5030	38840	6940	10180	14	
	11	82670	6820	8430	31430	78540	85220	5950	46980	7320	11910	13	
	12	83920	6560	8120	9970	66010	88930	6270	49750	7430	12560	12	
	13	82670	6820	7250	8950	47770	85220	5950	46980	7320	11910	11	
	14	78310	6360	5880	7280	27300	75200	5030	38840	6940	10180	10	
	15	68090	4990	4100	5040	7560	57900	3640	25950	6030	7950	9	
	16	41590	2680	2170	2430	3000	29210	1850	9630	3680	4990	8	
DEC 21	8	30740	1790	8780	29540	38340	22770	1300	5440	2410	3760	16	DEC
	9	65150	4190	8700	51680	74330	56760	3070	21040	5110	7090	15	
	10	77700	5580	8920	46160	83200	75990	4410	33810	6090	9130	14	
	11	82870	6040	7570	29850	78920	86730	5280	41900	6500	10620	13	
	12	84330	5770	7400	8950	66850	90600	5580	44660	6610	11190	12	
	13	82870	6040	6540	8060	48910	86730	5280	41900	6500	10620	11	
	14	77700	5580	5180	6500	28550	75990	4410	33810	6090	9130	10	
	15	65150	4190	3400	4320	8870	56760	3070	21040	5110	7090	9	
	16	30740	1790	1390	1660	1970	22770	1300	5440	2410	3760	8	
				NORTHWEST VERTICAL (LUX)	WEST VERTICAL (LUX)	SOUTHWEST VERTICAL (LUX)							

Table 2. Daylight Availability for Denver, Colorado (Diffuse Vertical)

A	B	C	D	E	F	G	H	I	J	K	L	M	N
	TIME	NORTH VERTICAL DIFFUSE CLEAR (LUX)	NORTHEAST VERTICAL DIFFUSE CLEAR (LUX)	EAST VERTICAL DIFFUSE CLEAR (LUX)	SOUTHEAST VERTICAL DIFFUSE CLEAR (LUX)	SOUTH VERTICAL DIFFUSE CLEAR (LUX)		TIME	NORTH VERTICAL DIFFUSE CLEAR (LUX)	NORTHEAST VERTICAL DIFFUSE CLEAR (LUX)	EAST VERTICAL DIFFUSE CLEAR (LUX)	SOUTHEAST VERTICAL DIFFUSE CLEAR (LUX)	SOUTH VERTICAL DIFFUSE CLEAR (LUX)
JAN 21	7	0	0	0	0	0	FEB	7	1260	2720	4910	4480	2230
	8	1740	3020	6100	7040	4880		8	2780	5310	8850	9330	6470
	9	2410	3760	8400	10210	8520		9	3150	5390	10100	11450	9380
	10	2480	4040	7950	10660	10000		10	3040	4990	9380	11740	10780
	11	2130	3740	6640	10350	10830		11	2600	4420	7710	11270	11560
	12	1580	3150	5000	9790	11400		12	1920	3600	5740	10610	12340
	13	2130	2550	4260	8010	10830		13	2600	2870	4780	8530	11560
	14	2480	1980	3400	6080	10000		14	3040	2220	3770	6480	10780
	15	2410	1510	2460	3870	8520		15	3150	1980	2830	4650	9380
	16	1740	1220	1490	2070	4880		16	2780	1850	2030	3130	6470
	17	0	0	0	0	0		17	1260	1100	1040	1240	2230
MAR 21	6	0	0	0	0	0	APR	6	2930	5930	7440	4790	2170
	7	2880	6250	8770	7570	3980		7	4640	9610	11550	9660	4680
	8	3990	7740	11030	10860	7230		8	5360	10200	12720	11850	7220
	9	4110	7240	11510	12240	9600		9	5300	9260	12800	12790	9240
	10	3780	6020	10990	12930	11440		10	4870	7590	12420	13780	11320
	11	3300	5240	8970	12490	12470		11	4310	6230	10600	14040	13310
	12	2490	4190	6420	11660	13660		12	3390	4950	7080	12790	15330
	13	3300	3280	5220	8820	12470		13	4310	3830	5570	8870	13310
	14	3780	2500	4020	6510	11440		14	4870	3330	4320	6440	11320
	15	4110	2630	3150	5150	9600		15	5300	3480	3480	5290	9240
	16	3990	2520	2440	3790	7230		16	5360	3250	2800	4020	7220
	17	2880	1920	1670	2250	3980		17	4640	2660	2150	2670	4680
	18	0	0	0	0	0		18	2930	1820	1490	1640	2170
MAY 21	5	1550	4090	3730	1390	1030	JUN	5	2780	5730	4990	2320	1540
	6	5130	8660	9360	6380	3150		6	6100	9710	10130	6910	3490
	7	6430	11360	12580	10250	5200		7	7350	12260	13210	10610	5470
	8	6460	12130	13910	12530	6930		8	7180	13220	14660	13060	7000
	9	6300	10930	13780	13110	8700		9	6900	11860	14350	13410	8810
	10	5880	9090	13120	13670	10460		10	6460	9630	12990	13100	9900
	11	5260	7050	11530	14470	12750		11	5840	7380	10690	13050	11030
	12	4410	5570	7480	12480	15270		12	5250	5970	7530	10330	12770
	13	5260	4460	5770	8170	12750		13	5840	5130	5980	7680	11030
	14	5880	4380	4690	6440	10460		14	6460	5110	5160	6570	9900
	15	6300	4290	3880	5320	8700		15	6900	4810	4390	5480	8810
	16	6460	3850	3200	4040	6930		16	7180	4230	3680	4160	7000
	17	6430	3460	2700	3010	5200		17	7350	3900	3070	3220	5470
	18	5130	2710	2040	2110	3150		18	6100	3150	2310	2340	3490
	19	1550	970	1200	1180	1030		19	2780	1510	1520	1480	1540
JUL 21	5	1700	4260	3870	1500	1080	AUG	5	0	0	0	0	0
	6	5230	8770	9430	6430	3180		6	3010	6050	7520	4870	2220
	7	6500	11420	12600	10250	5210		7	4680	9700	11600	9700	4680
	8	6500	12190	13940	12530	6890		8	5390	10250	12750	11860	7200
	9	6330	10990	13800	13090	8650		9	5330	9300	12820	12790	9200
	10	5920	9150	13140	13650	10400		10	4900	7640	12450	13780	11290
	11	5290	7080	11590	14530	12740		11	4330	6250	10650	14090	13330
	12	4430	5580	7500	12500	15320		12	3400	4960	7070	12830	15400
	13	5290	4450	5760	8120	12740		13	4330	3840	5570	8850	13330
	14	5920	4400	4680	6420	10400		14	4900	3350	4320	6430	11290
	15	6330	4310	3880	5310	8650		15	5330	3500	3480	5280	9200
	16	6500	3870	3200	4030	6890		16	5390	3270	2800	4020	7200
	17	6500	3500	2720	3020	5210		17	4680	2680	2160	2680	4680
	18	5230	2750	2060	2130	3180		18	3010	1850	1510	1660	2220
	19	1700	1020	1230	1210	1080		19	0	0	0	0	0
SEP 21	6	70	1010	3580	990	70	OCT	6	0	0	0	0	0
	7	2940	6370	8880	7660	4020		7	1210	2600	4760	4360	2150
	8	4030	7810	11080	10880	7230		8	2750	5230	8770	9270	6430
	9	4140	7290	11530	12240	9580		9	3120	5340	10060	11440	9380
	10	3800	6050	11030	12950	11430		10	3020	4960	9350	11730	10770
	11	3310	5270	9010	12530	12490		11	2590	4410	7680	11260	11550
	12	2490	4210	6430	11690	13710		12	1920	3590	5730	10600	12320
	13	3310	3280	5220	8910	12490		13	2590	2860	4770	8530	11550
	14	3800	2500	4020	6490	11430		14	3020	2230	3770	6480	10770
	15	4140	2640	3160	5150	9580		15	3120	1970	2820	4630	9380
	16	4030	2540	2440	3800	7230		16	2750	1830	2010	3100	6430
	17	2940	1040	1680	2270	4020		17	1210	1070	1020	1200	2150
	18	70	820	670	830	70		18	0	0	0	0	0
NOV 21	8	1720	2960	6020	6980	4820	DEC	8	1240	1980	4570	5500	3810
	9	2400	3730	8350	10170	8490		9	2090	3100	7310	9140	7710
	10	2470	4020	7930	10640	9990		10	2200	3540	7130	9900	9380
	11	2130	3730	6630	10340	10820		11	1850	3380	5980	9690	10240
	12	1580	3150	4990	9790	11480		12	1310	2930	4490	9170	10880
	13	2130	2550	4250	8000	10820		13	1850	2350	3870	7510	10240
	14	2470	1990	3390	6080	9990		14	2200	1790	3120	5670	9380
	15	2400	1510	2450	3860	8490		15	2090	1290	2220	3460	7710
	16	1720	1200	1470	2040	4820		16	1240	850	1120	1430	3810
			NORTHWEST VERTICAL (LUX)	WEST VERTICAL (LUX)	SOUTHWEST VERTICAL (LUX)					NORTHWEST VERTICAL (LUX)	WEST VERTICAL (LUX)	SOUTHWEST VERTICAL (LUX)	

Illuminances are to be read in the following way. The first value in column C of Table 1 (46,110 lux) is the instantaneous direct normal clear-day (defined below) illuminance at exactly 8:00 a.m. (column B) on January 21 (column A) of any year. Similarly, the instantaneous, direct normal, clear-day illuminance at 8:00 a.m. on February 21 is 69,730 lux. Linear interpolations can be used to determine illuminances at times between two on-the-hour values or for a given hour on days between the 21st days of succeeding months.

Columns C through L are headed by a collective that includes illuminance type (direct, diffuse, global), orientation (normal, vertical, horizontal), and sky condition (clear, overcast). These are defined as follows:

Illuminance Type

Direct -- unscattered light, direct from the sun
Diffuse -- sky-scattered light
Global -- direct plus diffuse plus ground-scattered light

Orientation

Normal -- perpendicular to direct sun line
Vertical -- perpendicular to earth (normal window)
Horizontal -- in plane of earth (flat-roof skylight)

Sky Condition

Clear -- Less than 30% cloud cover and unobstructed sun
Overcast -- Greater than 70% cloud cover and obstructed sun

Column headings for three surface directions (northwest, west, southwest) are given along the bottom of the table and correspond to time in colum M. Illuminance type and sky condition are identical to those at the top of the column (i.e., global clear for Table 1, diffuse clear for Table 2). Time values for these directions are read from column M for the clear-day values in Table 1. For example, clear-day illuminance on a west-facing vertical surface at 6:00 a.m. on April 21 is 2270 lux (Table 1, column F).

SUNLIGHT AVAILABILITY

Sunlight availability data provide a measure of the fraction of time the sun can be considered unobstructed. Tables 3 and 4 for Denver, Colorado, give a sample of the data. They are presented in hourly, monthly, and annual formats and give a designer an estimate of the portion of time the building will operate under clear or overcast conditions.

It is sometimes important to have an estimate of the portion of a given time period (day, month, year) that the sky is clear or overcast. Knowing, for example, that the sky is clear for only 40% of the time, a designer might want to consider daylighting concepts and ideas that work well in overcast climates. Effects due to climate differences are well understood by architects; daylighting concepts used in Italy are different from those used in England.

The National Oceanic and Atmospheric Administration (NOAA) has been the traditional source of sunlight availability data. Its data, often called percent sun, are based on a dawn-to-dusk measurement of the amount of daily sunlight. To be considered sunny, a time interval must have a minimum of 200 watts of radiation per square meter (for example, approximately 22,000 lux of global horizontal illuminance at noon on June 21). With this illuminance level, shadows are clearly distinguished.

Sunlight availability data (clear sky conditions) are presented in two formats for daylighting calculations. The first (Table 3) contains hourly sunlight availability fractions; listed values are the fractions of each hour of the year, from dawn to dusk.

In Table 3, "hour, solar" defines the particular hour, in solar time, for which monthly average values have been determined; the sun is due south (or north in southern latitudes) at noon. The sunlight availability fractions for each hour of each month (columns B through M) are ratios of the actual number of minutes of sunshine to the maximum possible minutes of sunlight in the hour. For most hours, the denominator is 60 minutes. Dawn and dusk hours, however, can have fewer than 60 minutes depending upon when the sun rises or sets.

Table 3. Sunlight Availability for Denver, Colorado

A	B	C	D	E	F	G	H	I	J	K	L	M	N	O
HOUR, SOLAR	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	ANNUAL FRACTION	ANNUAL HOURS
05:00-06:00	0.000	0.000	0.000	.339	.836	.782	.875	.376	0.000	0.000	0.000	0.000	.537	98.3
06:00-07:00	0.000	.146	.792	.754	.804	.790	.894	.823	.849	.288	0.000	0.000	.672	187.5
07:00-08:00	.621	.627	.805	.761	.790	.810	.911	.824	.822	.853	.729	.752	.777	283.5
08:00-09:00	.732	.642	.911	.755	.804	.818	.913	.830	.831	.860	.749	.798	.797	290.8
09:00-10:00	.754	.678	.843	.758	.786	.821	.896	.836	.846	.864	.744	.772	.801	292.3
10:00-11:00	.775	.750	.872	.764	.792	.823	.877	.852	.871	.851	.764	.784	.815	297.6
11:00-12:00	.818	.711	.829	.766	.796	.837	.864	.791	.866	.847	.812	.810	.813	296.7
12:00-13:00	.839	.721	.789	.734	.758	.794	.879	.754	.859	.852	.776	.822	.799	291.5
13:00-14:00	.854	.739	.745	.707	.717	.769	.814	.752	.861	.860	.763	.845	.786	286.9
14:00-15:00	.829	.716	.726	.675	.684	.774	.741	.710	.821	.854	.748	.878	.764	278.7
15:00-16:00	.831	.715	.704	.649	.649	.715	.641	.711	.797	.865	.747	.861	.741	270.3
16:00-17:00	.736	.731	.693	.623	.627	.694	.662	.724	.748	.855	.760	.816	.723	263.8
17:00-18:00	0.000	.150	.679	.639	.618	.712	.756	.718	.774	.276	0.000	0.000	.582	162.4
18:00-19:00	0.000	0.000	0.000	.227	.618	.699	.796	.335	0.000	0.000	0.000	0.000	.448	82.0
MONTHLY AVERAGE	.779	.610	.774	.654	.734	.774	.823	.717	.829	.760	.759	.814		
MONTHLY FRACTION	.779	.618	.735	.654	.669	.677	.720	.713	.746	.760	.721	.814		
MONTHLY AVG. HOURS OF SUNLIGHT PER DAY	7.8	7.3	9.3	9.2	10.3	10.8	11.5	10.0	9.9	9.1	7.6	8.1		

Table 4. Sunlight Availability by Standard Work Year for Denver, Colorado

A STANDARD WORK YEAR	B JAN	C FEB	D MAR	E APR	F MAY	G JUN	H JUL	I AUG	J SEP	K OCT	L NOV	M DEC	N ANNUAL (SA_S)
07:00-16:00	.705	.644	.792	.732	.758	.795	.843	.788	.842	.799	.683	.732	.760
07:00-17:00	.708	.652	.783	.722	.746	.786	.827	.782	.834	.804	.690	.740	.756
07:00-18:00	.649	.610	.774	.716	.735	.780	.821	.777	.829	.760	.632	.678	.730
07:00-19:00	.599	.564	.715	.678	.726	.774	.819	.743	.765	.702	.584	.626	.691
08:00-16:00	.784	.700	.792	.730	.753	.796	.837	.784	.842	.856	.759	.814	.787
08:00-17:00	.779	.703	.782	.719	.740	.786	.820	.778	.832	.856	.759	.814	.781
08:00-18:00	.708	.653	.773	.712	.729	.779	.814	.773	.827	.803	.690	.740	.750
08:00-19:00	.649	.598	.708	.672	.720	.772	.813	.736	.758	.736	.632	.678	.706
09:00-16:00	.804	.709	.790	.726	.748	.794	.828	.779	.844	.857	.763	.821	.789
09:00-17:00	.796	.711	.779	.715	.735	.783	.810	.773	.833	.856	.762	.821	.781
09:00-18:00	.717	.655	.769	.707	.723	.776	.804	.768	.827	.798	.686	.739	.747
09:00-19:00	.652	.596	.699	.663	.714	.769	.804	.728	.752	.726	.624	.672	.700

The "monthly average" and "monthly fraction" values near the bottom of Table 3 represent typical monthly clear-sky fractions, calculated by two methods. Monthly average values are monthly ratios of average clear-sky minutes to total minutes of actual daylight occurring during the month. Monthly fraction values use NOAA's definition of dawn and dusk hours; each such hour is taken to be 60 minutes long, independent of the time of sunrise or sunset. Differences between monthly average values and monthly fraction values thus depend on how dawn and dusk hours are considered. For example, when the sun rises at 7:50 a.m., the maximum possible minutes of sunshine for the 7 a.m.-8 a.m. hour is 10 minutes. If skies are clear during those 10 minutes, a monthly fraction approach gives an hourly value of 1.0; a monthly average approach yields a value of 0.167, since 10 minutes is 1/6 hour. All hourly values in Table 3 are based on a monthly fraction approach.

The values along the bottom row of Table 3 represent average hours of sunlight (clear conditions) per day in the month in the column head. Division of monthly average hours of sunlight per day by monthly average sunlight fraction provides an estimate of the average number of hours between dawn and dusk during the month. For example, average hours of daylight in Denver for June (from column G) are 10.8/0.774 = 14 hours.

Columns N and O of Table 3 are headed "annual fraction" and "annual hours." Annual fraction values are summations of minutes of sunshine over the year for the hour in column A as a fraction of the total number of minutes of daylight in the year during that hour. For example, for the 11 a.m.-12 noon (1100-1200) hour in Denver, the sun shines 81.3% of the time. The annual hours values (column O) are the total number of sunshine hours during the year for the time period in column A. Total annual daylight hours for each hour in column A are equal to annual hours (column O) divided by annual fraction (column N). For most hours of column A, such as 1100-1200, the maximum total annual daylight hours equal 365.

A second format for sunlight availability data (Table 4) organizes the data according to a series of standard work years (SWY); each corresponds to a possible building operating schedule. Three groups of SWY data can be found in Table 4, each group with a different beginning hour of the SWY (column A). Beginning hours are 0700, 0800, and 0900; ending hours are 1600, 1700, 1800, and 1900, giving a total of 12 standard work years. The 0800-1700 SWY represents the 8 a.m. to 5 p.m. work day.

Values under each monthly heading (columns B through M) represent the fraction of the month that is clear during the SWY in column A. Column N, headed "annual (SA_S)," lists values of the annual fraction of time during the SWY in column A that skies are clear.

Predominant sky conditions can be determined, by inspection, from Tables 3 and 4 values using the following definitions:

Sky Condition	Sunlight Availability
Very clear	0.85 - 1.0
Clear	0.75 - 0.84
Average	0.65 - 0.74
Overcast	0.55 - 0.64
Very overcast	<0.55

Values in Table 3 show predominant sky conditions in Denver, Colorado, to be clear in March (monthly average = 0.774, column D) and average in April (monthly average = 0.654, column E). For a building with an SWY of 0800-1700 (8 a.m. - 5 p.m.), Table 4 indicates the annual predominant sky condition to be clear (0.781, column N). Monthly values for an SWY (columns B-M) can be used if, for example, building cooling requirements call for seasonal sun shading that will reduce sunlight availability for lighting in some months.

DAYLIGHTING UTILIZATION FRACTIONS (DUF)

Daylight utilization factors provide statistical information about the resource and are derived from daylight availability data. With these factors, a designer can estimate the portion of the year that daylight can replace or supplement artificial lighting.

Hourly daylight availability data have been analyzed to establish frequency distribution curves that represent best fits to a combination of a parabola and a straight line. Daylight utilization fractions (DUF) can be determined from the fitting parameters, based on the standard work year (SWY) concept. DUF is defined as the fraction of the time during the SWY that illuminance equals or exceeds a threshold value where the threshold illuminance would be defined as the exterior illuminance necessary to maintain a desired interior illuminance. A table of fitting parameters is provided for each city in the compendium, and a graph is added that plots DUF values for two sky conditions (diffuse clear, horizontal; global overcast, horizontal) and one SWY. Table 5 and Figure 1 are samples for Denver, Colorado.

FREQUENCY DISTRIBUTION FITTING PARAMETER TABLES

At low illuminance, DUF values are obtained by a parabolic fit to a plot of the number of days with a given maximum illuminance versus that illuminance. At high illuminance, the fit is linear. The illuminance at the point where the fit switches from parabolic to linear is called the changeover illuminance, E_{co}, and the DUF equations for illuminances below and above E_{co} are

$$(E_t < E_{co}) \text{ DUF} = D_{max} \{1 + [E_t^2/E_{co} (E_{co} - 2E_{max})]\} \tag{1}$$

$$(E_t > E_{co}) \text{ DUF} = [2D_{max}/(E_{co} - 2E_{max})] (E_t - E_{max}) \tag{2}$$

E_t is the threshold illuminance value for the calculated DUF, and D_{max} is the maximum value of DUF for the SWY under study. E_{max} is the maximum exterior illuminance for the sky condition, SWY, and aperture orientation.

Frequency distribution parameters are organized (Table 5) for calculation of DUF for 12 SWY listed in column A. Columns B, C, and D define illuminance types (direct, diffuse, global), sky conditions (clear or overcast), and receiver surface orientations (normal or horizontal) that can be chosen, respectively. Fitting parameters for use in Equations (1) and (2) are found in columns E (E_{co}), F (D_{max}), and G (E_{max}). The G/d value in column H (actually labeled G/D) is the ratio of global-to-diffuse illuminance on a horizontal surface; it is used to approximate exterior threshold illuminance for a diffuse-sky condition. E_{mean} (column I) is mean exterior illuminance; DUF is approximately 0.5 when $E_t = E_{mean}$.

Table 5. Daylight Utilization Fraction (DUF) Data for Denver, Colorado

A	B	C	D	E	F	G	H	I
	ILLUMINANCE	SKY CONDITION	ORIENTATION	E-CO	D-MAX	E-MAX	G/D	E-MEAN
(0700-1600)	DIRECT	CLEAR	NORMAL	96290	.975	96310		76010
	DIFFUSE	CLEAR	HORIZONTAL	6380	.975	16720	5.744	9520
	GLOBAL	CLEAR	HORIZONTAL	31040	.975	100250	5.744	54670
	GLOBAL	OVERCAST	HORIZONTAL	10	.975	35360		14920
(0700-1700)	DIRECT	CLEAR	NORMAL	96290	.955	96310		72620
	DIFFUSE	CLEAR	HORIZONTAL	5960	.955	16720	5.598	9170
	GLOBAL	CLEAR	HORIZONTAL	21090	.955	100250	5.598	51340
	GLOBAL	OVERCAST	HORIZONTAL	10	.955	35360		14070
(0700-1800)	DIRECT	CLEAR	NORMAL	96290	.910	96310		67930
	DIFFUSE	CLEAR	HORIZONTAL	5560	.910	16720	5.509	8630
	GLOBAL	CLEAR	HORIZONTAL	14040	.910	100250	5.509	47570
	GLOBAL	OVERCAST	HORIZONTAL	10	.910	35360		13110
(0700-1900)	DIRECT	CLEAR	NORMAL	96290	.859	96310		62790
	DIFFUSE	CLEAR	HORIZONTAL	4920	.859	16720	5.501	7990
	GLOBAL	CLEAR	HORIZONTAL	12320	.846	100250	5.501	43930
	GLOBAL	OVERCAST	HORIZONTAL	10	.859	35360		12140
(0800-1600)	DIRECT	CLEAR	NORMAL	96290	1.000	96310		80150
	DIFFUSE	CLEAR	HORIZONTAL	6840	1.000	16720	5.908	9940
	GLOBAL	CLEAR	HORIZONTAL	42940	1.000	100250	5.908	58750
	GLOBAL	OVERCAST	HORIZONTAL	310	1.000	35360		15960
(0800-1700)	DIRECT	CLEAR	NORMAL	96290	.975	96310		76010
	DIFFUSE	CLEAR	HORIZONTAL	6380	.975	16720	5.744	9520
	GLOBAL	CLEAR	HORIZONTAL	31040	.975	100250	5.744	54670
	GLOBAL	OVERCAST	HORIZONTAL	10	.975	35360		14920
(0800-1800)	DIRECT	CLEAR	NORMAL	96290	.924	96310		70580
	DIFFUSE	CLEAR	HORIZONTAL	5950	.924	16720	5.645	8900
	GLOBAL	CLEAR	HORIZONTAL	22770	.924	100250	5.645	50250
	GLOBAL	OVERCAST	HORIZONTAL	10	.924	35360		13800
(0800-1900)	DIRECT	CLEAR	NORMAL	96290	.868	96310		64790
	DIFFUSE	CLEAR	HORIZONTAL	5310	.868	16720	5.636	8180
	GLOBAL	CLEAR	HORIZONTAL	20970	.854	100250	5.636	46090
	GLOBAL	OVERCAST	HORIZONTAL	10	.868	35360		12690
(0900-1600)	DIRECT	CLEAR	NORMAL	96290	1.000	96310		82060
	DIFFUSE	CLEAR	HORIZONTAL	7390	1.000	16720	6.087	10140
	GLOBAL	CLEAR	HORIZONTAL	56220	1.000	100250	6.087	61710
	GLOBAL	OVERCAST	HORIZONTAL	2850	1.000	35360		16720
(0900-1700)	DIRECT	CLEAR	NORMAL	96290	.972	96310		77250
	DIFFUSE	CLEAR	HORIZONTAL	6850	.972	16720	5.895	9650
	GLOBAL	CLEAR	HORIZONTAL	40830	.972	100250	5.895	56860
	GLOBAL	OVERCAST	HORIZONTAL	10	.972	35360		15480
(0900-1800)	DIRECT	CLEAR	NORMAL	96290	.917	96310		71150
	DIFFUSE	CLEAR	HORIZONTAL	6370	.917	16720	5.782	8950
	GLOBAL	CLEAR	HORIZONTAL	31580	.917	100250	5.782	51780
	GLOBAL	OVERCAST	HORIZONTAL	10	.917	35360		14190
(0900-1900)	DIRECT	CLEAR	NORMAL	96290	.856	96310		64790
	DIFFUSE	CLEAR	HORIZONTAL	5700	.856	16720	5.772	8160
	GLOBAL	CLEAR	HORIZONTAL	29550	.841	100250	5.772	47100
	GLOBAL	OVERCAST	HORIZONTAL	10	.856	35360		12940

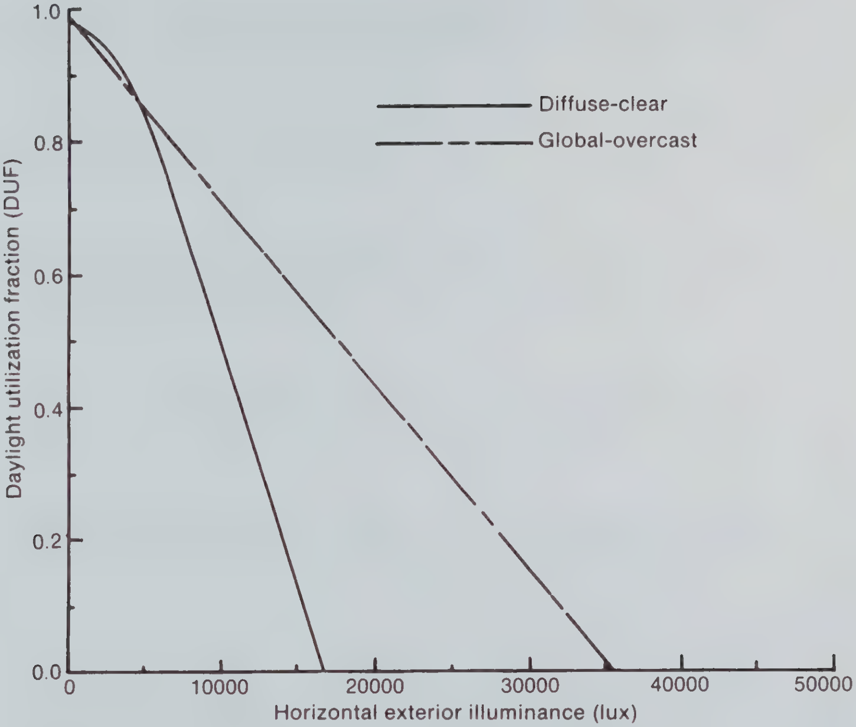


Figure 1. DUF chart for Denver, Colorado, SWY (0800-1700)

A designer usually considers the daylighting implications of an aperture with a particular glazing type and orientation. Table 6 indicates which line of fitting parameters, for a selected SWY, should be used to compute the relevant daylight utilization fractions for selected glazings and orientations.

DAYLIGHT UTILIZATION FRACTION GRAPHS

A DUF graph (Figure 1) for each city contains two curves, one of diffuse illuminance for a clear sky and one of global illuminance for an overcast sky, both on an exterior horizontal surface. An SWY has been selected to typify the 12 SWY, that of 0800 - 1700 (8:00 a.m. to 5:00 p.m.). The abscissa (X-axis) is exterior illuminance on a horizontal surface, and the ordinate (Y-axis) is the associated DUF. For example, with an overcast sky (broken curve), an exterior

Table 6. Daylight Aperture and Glazing Combinations for Use with Table 5

Glazing	Aperture	Analyzing	Use (Illum., sky, orient.)
Transparent	Any [a]	Clear sky	Diffuse, Clear, Horizontal
		Overcast sky	Global, Overcast, Horizontal
Translucent	Any [a]	Clear sky	Global, Clear, Horizontal
		Overcast sky	Global, Overcast, Horizontal
	Heliostat	Clear sky	Direct, Clear, Normal
		Overcast sky	Global, Overcast, Horizontal

[a] Aperture type (vertical, angled, horizontal, monitor, sawtooth, etc.) is not critical.

illuminance of 20,000 lux corresponds to a DUF of 0.43. Thus, for a (0800-1700) SWY in Denver, Colorado, available illuminance on an exterior horizontal surface will equal or exceed 20,000 lux 43% of the time.

The two curves intercept the ordinate at D_{max}, the maximum daylight utilization fraction (tabulated in column F of Table 5). Each curve intercepts the abscissa at E_{max}, the maximum exterior illuminance corresponding to the sky condition (tabulated in column G of Table 5). D_{max} does not intercept the ordinate at 1.0 since, for a small portion of the year (about 3% in Denver), daylight is not available during the 0800-1700 SWY.

REFERENCES

ASHRAE, 1985. *ASHRAE Handbook: 1985 Fundamentals.* Atlanta: American Society of Heating, Refrigerating, and Air-Conditioning Engineers.

Robbins, C., 1986. *Daylighting Design and Analysis.* New York: Van Nostrand Reinhold Co.

Passive Solar Journal, 3(2), 207-210 (1986)

Book Review

Solar Architecture: The Direct Gain Approach

Timothy E. Johnson. New York: McGraw-Hill, Inc. 1981.
218 pp. ISBN 0-07-032598-7. Hardbound. $21.50.

The title promises both a holistic and a focused look at one popular approach to passive solar heating. The author's reputation (and an elegant color photo on the jacket) leads the reader to expect high-tech overtones. I believe most readers who are knowledgable about solar will find what was promised. We know that Tim Johnson has worked with both heat mirror and phase-change materials; these are thoroughly and tastefully integrated in this book's coverage of the direct gain approach. The book is certainly not merely a sales pitch for these products--in fact, I wish that a section on their economic advantages had been included.

Although the book is about architecture, not just solar heating performance, I doubt that it is for the layperson. If all the technical terms used were explained from scratch, the book would be considerably thicker than its 218 pages. Architects will welcome a number of discussions on less technical topics. Microclimates, for example, are included because of how they affect the windows that characterize direct-gain buildings. The discussion of microclimates is concise but informative, albeit with a New England flavor. (After all, regionalism is expected with passive solar, rather like having clam chowder when in Boston. The regionalism becomes parochial only in the choice of the very few contemporary houses that are presented.)

In discussing plan organization, Johnson encourages an open plan approach for spreading the radiance of direct gain throughout a building. He presents comfort issues in great detail, thereby making a convincing case for radiant transfer relative to convective transfer, an argument that will help sell almost any passive solar approach. For the more fanatical, there is even a nomograph for converting globe thermometer readings to mean radiant temperature.

With regard to another architectural issue, daylighting, Johnson gives well-known, quick rules of thumb for sidelighting (but not skylighting?) and some nonnumerical suggestions for glare avoidance. He provides thoughtful coverage of the conflicts between the advantages of diffusing glass (uniform mass irradiation) and its disadvantages (glare, view interference). And finally, he includes a step-by-step technical performance section that begins as it should, with the designer formulating a spatial organization concept.

The more focused presentations for solar technocrats cover some principal issues in direct gain, including windows, mass, auxiliary heating, temperature swing, and approximate yearly performance. Concerning windows, Johnson notes: "Windows are an unassailably dramatic building element. Perhaps this is what excites architects and owners alike about direct-gain passive solar heating." What follows is a detailed guide through the transmissivity and heat loss of many glazing materials, complete with average daily net heating energy per square foot of window in Boston, Madison, and Seattle, for three glazing systems. Not surprisingly, heat mirror does very well, almost equivalent to double glass with night insulation. Johnson also discusses approaches to night insulation, framing to accommodate thermal expansion, shading, natural ventilation, and daylighting with less glare. The weakness of his discussion of windows, I thought, was a discussion of where to place the heat mirror relative to double-glazed windows at various orientations. An illustration of this placement would have greatly aided the text.

The issue of mass is concisely presented, including an argument for masonry surfaces 5 to 7 times window areas at 50% SSF or more. Discussions of room absorptance for various configurations and of secondary mass surfaces are particularly informative. Johnson presents phase-change materials, but their important characteristics are buried within the text. A table with characteristics such as fusion temperatures, weights per square foot, and Btu of storage per square foot, would have been a welcome addition. A concise little section on sun tempering for ordinary-weight construction presents the lightweight contrast to the foregoing glass and mass case.

The section on auxiliary heat focuses on wood stoves and some of their architectural consequences, as well as suggestions (complete with design procedure) for how to link off-peak electric resistance ceiling heat with phase-change materials. An example shows that this combination need cost no more than the forced-air furnace it replaces.

The technical climax of the book is the presentation of graphical thermal comfort design methods based on Philip Niles' work at Cal Poly San Luis Obispo. After opening with a design-issue review of direct gain characteristics, Johnson discusses the matter of thermal swing. I found the subsequent 8-step process intriguing, but it uses a lot of unfamiliar terms. The process supposedly takes only a few minutes, but the terminology and need for local data do not promise expedience. On the other hand, one of several useful (though dated) appendices presents the TI59 program for this process. Since each month may have a different thermal swing, one can choose between doing all of the heating months or choosing one as representative. This book explains why March is recommended.

The design example is an old Boston loft-type converted warehouse with an astonishing mass thickness and ratio of surface-to-glass (heat mirror) area. The result is a March clear-day temperature swing of 9.3°F (5.2°C) (assuming concrete surfaces are directly exposed to the space).

Johnson also presents a moderately fast March-based approximation for annual auxiliary energy needed, with fuel savings. This method assumes 100% utilization of transmitted insolation. For the above Boston example, the fast method yields 102 million Btu annual auxiliary heat compared with 159 million Btu for the slower monthly method. (*Volume 3* of the *Passive Solar Design Handbook* gives 217 million Btu using reference design DGC3 in the annual LCR method.)

In all, I was pleased with the book and will use parts of it in the future. It is a blend of architectural implications and technical facts that makes it a useful companion to *Volume 3*, with a slant that differs from Mazria's *Passive Solar Energy Book*. The designer of direct gain systems will appreciate having this book on the reference shelf.

Review by John Reynolds
Department of Architecture
University of Oregon
Eugene, Oregon 97403

Passive Solar Journal, 3(2), 211-212 (1986)

About the Contributors

Sara Butler is an Associate Professor of Retailing in the Department of Home Economics and Consumer Sciences, Miami University (Ohio). With a background in clothing and textiles, she has focused on research integrating this discipline with energy conservation.

Jay Burch is a Senior Physicist in the Buildings Research Branch at the Solar Energy Research Institute. He has been involved in monitoring for 6 years. Currently his research focuses on short-term tests in buildings (both residential and commercial) for diagnostic application.

Jeffrey Cook is a Professor of Architecture at Arizona State University, where he heads the graduate research program in the College of Architecture and Environmental Design. He has also focused on passive and hybrid solutions to comfort in overheated climates, and has published and lectured widely on architectural, planning, and aesthetic issues of appropriate response to climate, local materials, and skills. He is a recipient of the Passive Pioneer Award of the American Solar Energy Society in 1984 to honor his early and persistent educational activities.

Denise Guerin is an Assistant Professor of Interior Design in the Department of Home Economics and Consumer Sciences, Miami University (Ohio). She has studied the effects of passive solar design on interior environments for 10 years and has presented numerous papers at passive solar conferences.

James Hedstrom is a Staff Member in the Solar Energy Section at Los Alamos National Laboratory. He has been involved in solar energy analysis and experiments for 10 years. In particular, he has wide experience in active and passive systems including the design and analysis of the active solar heating and cooling systems at the Oppenheimer Study Center.

Bruce Hunn is Head of the Conservation and Solar Energy Program in the Center for Energy Studies at the University of Texas at Austin. He is responsible for research programs in passive/hybrid cooling, energy analysis of buildings, and HVAC systems analysis. He was formerly Associate Group Leader of the Solar Energy Group at Los Alamos National Laboratory where the research in this paper was conducted. He is active in ASHRAE and is serving as the 1986 Chair of the American Solar Energy Society.

Kerri Hunter, former Staff Engineer in the Buildings Research Branch at the Solar Energy Research Institute, is currently with the Architects Design Collaborative, Parkville, Missouri. In her present position she is responsible for building design including daylighting and energy analysis.

John Peterson is a Research Engineer in the Conservation and Solar Energy Program at the Center for Energy Studies at the University of Texas at Austin. He was formerly a Staff Member in the Solar Energy Group at Los Alamos National Laboratory. His areas of research include desiccant and evaporative cooling systems analysis and HVAC systems analysis. John is active in ASHRAE.

John Reynolds is a Professor of Architecture at the University of Oregon. A practicing architect, he is a principal in the firm Equinox Design, Incorporated. John is currently Vice Chair of the American Solar Energy Society.

Claude Robbins, a Senior Engineer in the Buildings Research Branch at the Solar Energy Research Institute, is a task leader for daylighting research. He has published 2 books and over 100 journal articles and papers on daylighting, lighting, and energy use.

Join the

American Solar Energy Society

Help yourself while you help the cause of Solar Energy.

We invite you to become a member of ASES and join other solar professionals united to advance the cause of U.S. energy independence by adoption of solar energy technologies.

Here are some of the services you will come to enjoy as an ASES member:

- Regular forums for the exchange of technical ideas between professional collegues.
- ***Advances in Solar Energy,*** a compendium of the latest R&D developments in solar energy, authored by select ASES members and published annually by the Society for distribution worldwide.
- Two major technical conferences each year (with published proceedings) presented especially for ASES members and offered to them at special reduced prices.
- A quarterly ***Passive Solar Journal*** in which ASES members may publish their ideas and keep abreast of state-of-the-art developments in this field.
- A quarterly Newsletter with a special technical feature in each issue.
- A wide variety of technical publications offered to ASES members at special reduced prices.
- Special committees and councils providing ASES members the means to voice their views and collectively establish positions on given issues related to solar energy.

ASES needs your support. With the world's diminishing attention to renewable energy development, it is more important than ever that our nation's number one professional solar society remain strong. We can make great strides with your help. Show your commitment and join ASES today. Simply fill in the application below and submit it to the **American Solar Energy Society**; 2030 17th St.; Boulder, CO 80302. For additional information call (303) 443-3130.

ASES Membership Application

Name ______________________________
Title ______________________________
Company (if applicable) ______________________________
Address ______________________________
____

Please register me as a:

☐ Full Member   ASES only ($50)
☐ ASES + ISES* member ($85)
☐ Full member and subscription to *Passive Solar Journal* ($75)
☐ Check enclosed (payable to ASES)

Signature:
____

☐ Visa ☐ Mastercard ☐ AE

No. ______________________ Exp. Date __________

*International Solar Energy Society   ASES international affiliate. (Dues include subscription to ***Solar Energy Journal***.)

CODEN: PASJDF 3(3) i-vi, 213-326 (1986)
ISSN: 0277-6456

Passive Solar Journal

Volume 3, Number 3, 1986

BOSTON ARCHITECTURAL CENTER
LIBRARY
320 NEWBURY ST.
BOSTON, MA. [illegible]

Heating, Cooling, and Lighting for Buildings

PASSIVE SOLAR JOURNAL

Sponsorship. *Passive Solar Journal* is the official journal of the Passive Architecture and Construction Division of the American Solar Energy Society, Inc.

Indexing and Abstracting Services. Articles published in *Passive Solar Journal* selectively appear in all major indexing and abstracting publications.

Manuscript Preparation and Submission. See inside back cover.

Subscription Information. *Passive Solar Journal* (ISSN: 0277-6456) is published in four numbers by Marcel Dekker, Inc., 270 Madison Avenue, New York, New York 10016. The subscription rate for Volume 3 (1986), is as follows:

Non-Member Institutions	$ 125.00
Society Member Institutions	90.00
ASES Membership Dues	150.00
Non-Member Individuals	47.50
Society Member Individuals	25.00
ASES Membership Dues	50.00

Your order must be prepaid by personal check or may be charged to MasterCard, VISA, or American Express. Please add $12.00 for surface postage outside the United States. For airmail to Europe, add $15.00; to Asia, add $19.00. Please mail payment with order to: Marcel Dekker, Inc., P. O. Box 11305, Church Street Station, New York, New York 10249.

Copyright © 1987 by Marcel Dekker, Inc. All rights reserved. Neither this work nor any part may be reproduced or transmitted in any form or by any means, electronic or mechanical, microfilming and recording, or by any information storage and retrieval systems without permission in writing from the publisher.

Authorization to photocopy items for internal or personal use, or the internal or personal use of specific clients, is granted by Marcel Dekker, Inc. for users registered with the Copyright Clearance Center (CCC) Transactional Reporting Service, provided that the base fee of $3.50 per copy is paid directly to CCC, 27 Congress Street, Salem, MA 01970. For those organizations that have been granted a photocopy license by CCC, a separate system of payment has been arranged. The fee code for users of the Transactional Reporting Service is: 0277-6456/86$3.50.

Contributions to this journal are published free of charge.

Passive Solar Journal

Official Journal of the Passive Architecture
and Construction Division of the
American Solar Energy Society, Inc.

BOSTON ARCHITECTURAL CENTER
LIBRARY
320 NEWBURY ST.
BOSTON, MA. 02115

Editor-in-Chief

ROBERT W. JONES
Los Alamos National Laboratory
Mail Stop J577
Los Alamos, New Mexico 87545

Assistant Editor

MELANIE BLAIN
Los Alamos National Laboratory

Production Editor

NANCY S. REECE
Solar Energy Research Institute
1617 Cole Boulevard
Golden, Colorado 80401

Consulting Editor

JEFFREY COOK
Arizona State University

Associate Editors

DENNIS A. ANDREJKO
State University of New York

J. DOUGLAS BALCOMB
Los Alamos National Laboratory

SUBRATO CHANDRA
Florida Solar Energy Center

EUGENE CLARK
Trinity University

JOHN W. HAYES
Marlboro College

MICHAEL J. HOLTZ
Architectural Energy Corp.

BION D. HOWARD
National Association of Home Builders

BRUCE D. HUNN
University of Texas

DONALD A. NEEPER
Los Alamos National Laboratory

CLAUDE ROBBINS
Architectural Energy Corp.

RICK SCHWOLSKY
Grafton Builders

ROBERT O. SMITH
Robert O. Smith & Associates

AIMS AND SCOPE

The **Passive Solar Journal** is the official journal of the Passive Architecture and Construction Division of the American Solar Energy Society, Inc., the United States Section of the International Solar Energy Society. This organization has sponsored major national and international passive conferences. The **Journal** is guided by a distinguished editorial board, an international panel of advisors, and expert peer reviewers.

The purpose of the **Passive Solar Journal** is to stimulate and support the flow and exchange of research and professional information. The **Journal** is intended to become the archival record and the standard international reference for the field, with principal directions and issues documented in illustrated and referenced presentations. Annual indexes provide detailed cross-reference access. The **Journal** contains full-length articles, book reviews, and opinions that meet the highest standards of verbal and graphic communication. The scope of subject matter is passive solar heating, passive cooling, and natural lighting plus related subjects including the following:

Advanced concepts
Building climatology
Codes and standards
Community planning
Component design
Computer methods
Conservation
Construction details
Control systems
Daylighting
Design tools
Direct gain
Domestic hot water
Earth coupling
Economic analysis
Education
Energy budgets
Energy storage
Evaporative cooling
Historical examples
Hybrid systems
Indirect gain
Indoor air quality
Instrumentation
Integration and optimization
Landscaping
Lifestyles and needs
Market development
Movable insulation
Phase change materials
Photovoltaic interface
Radiation resources
Retrofits
Roof ponds
Selective surfaces
Shading
Simulation
Sky radiation
Solar architecture
Solar greenhouses
Sunspaces
Testing and monitoring
Thermal comfort
Thermal networks
Thermosiphons
Trombe walls
Underground climate
Urban design
User evaluation
Ventilation
Window systems

ANNOUNCEMENT OF POSITION VACANCY

Senior Researcher
Center for Energy Research/Education/Service (CERES)

Ball State University
Muncie, Indiana 47306

Description:

Responsible for teaching a minimum of one and a maximum of two courses while conducting energy-related research in his/her chosen field. In addition will contribute to programmatic development of Research Agenda for the Center. Qualifications: grant solicitation and college level teaching experience, Ph.D. (or equivalent), interest in hybrid (cross-discipline) and specialized (single-discipline) research, suitability for tenure in related academic department. Ball State University, a state-supported school of 17,500 students, has 2,500 students at the master and doctoral levels. The Center is a unique university-wide administrative unit housed in a new 1.5 million dollar research and teaching facility.

Begin: July 1, 1987 or later. Salary open.

Review of applications will begin January 30, 1987 and continue until position is filled. Applications must include applicant's resume, interest in position, names and addresses of 3 to 5 references and statement of special qualifications. Full credentials will be required. Nominations, applications or inquiries should be addressed to Professor Robert J. Koester, Director, Center for Energy Research/Education/Service, Ball State University, Muncie, IN 47306.

Ball State University Practices Equal Opportunity in Education and Employment
Date Listed: 11-5-86

Passive Solar Journal
Volume 3, Number 3, 1986

Contents

Opinion/Solar Buildings Research: What are the Best Directions? 213
D. Neeper

Conservation and Solar Guidelines 221
J. D. Balcomb

The Air-core System for Thermal Storage 249
B. Howard

Natural Convection in a Passive Solar Building 277
A. Kirkpatrick, D. Hill, and K. Stokes

Passive Solar Buildings in Italy 291
G. Funaro

Book Review/The Sunspace Primer — A Guide for Passive Solar Heating 321
B. Howard

About the Contributors 325

Passive Solar Journal, 3(3), 213-219 (1986)

Opinion

Solar Buildings Research: What are the Best Directions?

Donald A. Neeper
Mail Stop J576
Loas Alamos National Laboratory
Los Alamos, New Mexico 87545

In a recent opinion article (Vol. 3, No. 1 of this journal), Murray Milne suggests that phrases like solar heating should be eliminated from the vocabulary, replaced by the term "competent design," and taken for granted. I don't disagree with Milne; it would be nice if all buildings were competently designed for their local climates. However, the notion of "competent" sometimes involves conflicting requirements for function, comfort, cost, and aesthetics. Furthermore, there may be more than one route to a given end, as illustrated, for example, by the fact that both insulation and solar gains can provide heating comfort with increased capital cost and lower life-cycle cost. Although we can all recognize a grossly incompetent design, it may never be possible to reach a consensus on exactly what constitutes competent design. Thus, the term "solar" may be needed to describe a particular class of buildings for the indefinite future. However, I suggest that we can soon drop the terms "active"

Copyright © 1986 by Marcel Dekker, Inc.

and "passive" as they relate to system design because good buildings will utilize some of each and some of neither. For example, an office building with roof-aperture daylighting, automatic control of solar and electric illumination, and architectural storage of evaporative night cooling is neither an "active" building nor a "passive" building; it is simply a solar building.

The number of energy-related choices available to the designer is large, but it may be exceeded by the number of constraints imposed by customers, laws, and markets. Choices increase as new methods and materials are developed; the best new methods and materials are those that also relieve some constraints. Therefore, I offer an opinion on the research that will provide the largest opportunities for wide use of solar buildings by increasing choices and decreasing constraints. I must first define what I mean by "solar" and "research."

By a "solar" building, I mean one that obtains much of its required heating, cooling, or lighting from its local natural environment. In this article, by the term "research" I mean the development of information, devices, materials, or products through the application of physical science. For this discussion, I have restricted the term "research" to laboratory activities. I do not mean that architectural experimentation, market evaluation, or the dissemination of information are less important. I simply wish to identify those elements of laboratory science that I believe will have the most favorable impact for solar buildings, without becoming embroiled in other arguments.

DESIGN RULES AND METHODS

The quantitative design rules and the methods underlying the commercial design tools for solar buildings originated largely in laboratory science. The thermal design of active systems and many passive heating systems is by now straightforward, albeit sometimes tedious. Some methods for the design of daylighting exist, although they are less well known. But the research job is not complete. Active systems, by their mechanical nature, are expensive, and passive systems often constrain the layout and orientation of the building. Furthermore, I venture the opinion that most existing buildings do not have the combination of southern exposure and floor plan that would easily accommodate a passive retrofit. If solar techniques are to have signficant national energy impact, they must be applicable to older buildings as well as to new construction. For those many cases in which established passive heating designs are not applicable, there is opportunity for research to discover the best combinations of active collection with passive distribution and storage. I suspect that these so-called "hybrid" systems will have greater utility than either the purely active or passive systems. As in passive design, hybrid systems will be most successful if they maximize the use of the building and its ordinary components to provide thermal comfort. For cooling and daylighting, too, there is still ample opportunity for the investigation of design rules. A building owner in Omaha cannot now easily determine whether window awnings, an attic radiant barrier, skylights, or an air conditioner will provide the greatest benefit. Research in these areas has been started; it should not be stopped.

HARDWARE: CRITERIA FOR IMPACT

Many energy products labeled as "solar" have recently sold for a price about four times greater than justified by their economic payback. Much of this price has been due to marketing practice. Solar products have been useful only for a narrow range of solar energy applications. Often, they have been sold in special stores or peddled by door-to-door salesmen whose knowledge has not gone beyond tax credits. Solar hardware has been installed by special crews that may or may not have understood what they were doing. For a large impact, it is necessary to have a large market. That is, almost every building potentially should be a solar building, and almost every builder potentially should be a solar builder. Solar systems and hardware will find larger markets if they meet certain market criteria such as if they:

- fit into the ordinary structure for distribution, marketing, and installation of building products;
- have multiple uses not limited to strictly solar applications;
- apply to the rehabilitation of older buildings;

- are modular, allowing the solar system to be purchased and enlarged a little at a time; and
- utilize the building itself to provide much of the system.

Research on new systems and new hardware should be conducted with these market criteria in mind. A building owner's reluctance to use something new can be overcome in time, but the facts of the marketplace will remain.

NEW HARDWARE: GLAZINGS

Most solar systems depend in one way or another on glazed apertures that are part of, or attached to, the building facade. Glazings permit solar gain for heating or lighting, and can be modified to reject solar gain for cooling load avoidance. Most buildings have windows, and there is increased interest in quality fenestration for energy conservation as illustrated by the growing market for low-emittance (low-e) glass in both new construction and replacement. By infusion into the window market, other new glazing materials can likewise find widespread acceptance. Glazings satisfy the above-listed criteria for marketability, but glass is an old material. What can new research accomplish?

Both Japanese and American researchers have shown that it is technically possible to make a dimmable glazing, that is, a glazing for which the transmission of solar radiation can be controlled at will. At present, the literature indicates that the Japanese are a step closer to commercialization than the Americans. A dimmable glazing should enable much greater use of daylighting (with consequent savings of energy for lighting and cooling) in commercial buildings, because the apertures could be large enough to permit daylighting under almost all weather conditions, while automatically restricting excessive gains during strong insolation. Although solar energy technicians may foresee daylighting and control of passive heating systems as the major applications of dimmable glazings, the stimulus for commercial production might come from the application as a convenience in view windows, where these glazings would prevent glare and discomfort. The solar market would therefore be part of a larger market.

Greatly improved thermal glazings are possible. Ordinary double glazing is rated at about R-2, meaning it has a thermal resistance of approximately 2 ft^2 h °F/Btu (0.35 m^2 K/W, or RSI 0.35). This can be increased to R-3 or R-4 (RSI 0.5 or 0.7) with the use of low-emittance coatings, but the low-e glazings that are now sold severely reduce the solar transmission. Thus, there is opportunity for research on better low-e coatings. However, researchers should aim well beyond the R-3 or R-4 window glazing. Various studies indicate that a window with a thermal resistance of R-8 (RSI 1.4) or greater, combined with a solar transmittance of 50% or greater, would have net heating benefits superior to that of an R-18 (RSI 3.2) insulated wall, even in a north-facing application in a cold, cloudy climate. One Swiss firm now advertises such a glazing. It employs two polymer films between glass, is about 4 in. (10 cm) thick, and reportedly requires occasional replacement of a desiccant breathing tube. My colleagues inform me that the thickness and breathing tube replacement make this glazing unacceptable to the American market, and that the stretched-film technology is unacceptable to the large American manufacturers, although it is used by several smaller window companies. In response, I can only note that small automobiles were also once regarded as unacceptable in the United States. There are a variety of ways to achieve a truly superior thermal glazing, and such a glazing would have solar benefits for almost all buildings. I cannot think of an area of solar energy research with greater potential payoff. To be sure, small fractions of the U.S. federally funded conservation and solar research programs are now directed toward improved thermal glazings; however, I see these fractions as small in proportion to the payoff.

NEW HARDWARE: THERMAL STORAGE

I have indicated that the best designs use the building itself to provide most of the system. Passive heating and cooling systems owe much of their economic and aesthetic success to the fact that they utilize floors and walls of the building for thermal storage. There is an opportunity to make greater use of the interior architectural surfaces for thermal storage through the application of phase-change materials (PCM). Standard materials such as masonry and water must change temperature in order to store energy (they are "sensible" heat storage materials). The amount of energy stored is thereby limited by both the allowable temperature swing of the building and by the ability of heat to diffuse into and out of the depth of the material. In contrast, PCMs usually absorb or release heat at a single temperature, and require a smaller volume than sensible materials. The smaller volume is at once a blessing and a curse. As a blessing, a Trombe wall of pure PCM could be about one-fourth the thickness of a masonry wall with equivalent performance. As a curse, the relatively small surface area of bulk PCM makes it difficult to transfer the heat into and out of storage if it must be both charged and discharged by exposure to temperatures within the room, as occurs in certain passive or hybrid systems.

One way to effectively extend the area of the PCM is to infuse it into all the exposed wall and ceiling surfaces of the building, thus permitting thermal storage to be distributed throughout the entire building. A few very limited calculations indicate that direct gain, convectively coupled sunspace, and night ventilation systems should work well with distributed PCM storage. Simple arguments indicate that approximately 40 Btu/ft^2 (450 kJ/m^2) is the upper limit of latent thermal capacity per unit area that can be utilized in distributed form. A small research project in the United States indicates that at least 30 Btu/ft^2 (340 kJ/m^2) can be obtained by impregnating gypsum wallboard with special, self-encapsulating waxes. Canadian workers have displayed samples of tile and other masonry materials similarly impregnated with fatty acids. One other U.S. project is directed toward finding a material that does not melt, but changes from one solid phase to another. If selection of the correct transition temperature, assurance of fire safety, and other practical questions are solved, there is a promise for architectural finish products that provide adequate thermal storage for heating and cooling as a consequence of the routine course of building construction. They could be sold in every lumber yard and installed by every builder.

Few studies have been conducted on the systematic impact of distributed PCM storage. For example, it appears that careful selection of the PCM transition temperature would enable ventilative cooling in locations where it is not possible with sensible storage. This apparent advantage of PCM occurs because the night ambient air temperature becomes low enough to remove heat from a PCM at fixed temperature, but not from sensible storage that must experience a large temperature change. Part of the research should therefore be a careful analysis to discover if these materials are as valuable as they appear to be, and to determine target values for their physical properties.

CONCLUSION

Many other research efforts might enable isolated improvements in the performance of solar buildings. However, a designer can incorporate natural lighting, heating, and cooling in almost any building--retrofit or new construction--by using the following either separately or in combination: design rules for hybrid systems, cooling load avoidance, and daylighting; materials for dimmable and thermal glazings; and materials for distributed PCM storage. Research on these topics can yield systems and products that meet the criteria for marketability. In short, those of us concerned with the technical aspects of solar buildings should bear marketability in mind. If we can't sell it for almost every building, we probably won't sell it at all. Right now, we're close to not selling it at all.

Passive Solar Journal, 3(3), 221-248 (1986)

Conservation and Solar Guidelines

J. Douglas Balcomb*
Los Alamos National Laboratory
Los Alamos, New Mexico 87545

Abstract

Guidelines are given for selecting R-values and infiltration levels, and determining the size of the solar collection area for passive solar buildings. The guidelines are based on balancing the incremental cost/benefit of conservation and passive solar strategies. Tables are given for 90 cities in the United States and the results are also displayed on maps. The procedures are developed in an appendix, which gives the cost assumptions used and explains how to develop different guidelines for different costs.

---

*Until October 1987, Distinguished Research Fellow, Solar Energy Research Institute, 1617 Cole Boulevard, Golden, Colorado 80401.

Copyright © 1986 by Marcel Dekker, Inc.

INTRODUCTION

Guidelines, even if they are only approximate, are very useful early in the design process. Often taking the form of rules of thumb evolved from experience, guidelines always involve a compromise between accuracy and simplicity of use. Guidelines lose their effectiveness if they are either too complex or too narrow in application; if the exceptions to a guideline are extensive, the guideline may be incorrectly applied too often. Good guidelines are perhaps the most difficult design tool of all to develop; ideally they are the ultimate distillation of sophisticated analysis tested against practical experience.

During the last few years, a conclusion has been expressed repeatedly: good passive solar design involves a balance of conservation and solar gains, and the proper balance depends on the climate. This conclusion is independently reached by cost/benefit studies using computer models and by practitioners designing and building across the country. Conservation makes the passive solar system's job easier; likewise, passive solar reduces the need for auxiliary heat well below levels attainable by conservation alone. Good thermal design consists of achieving a proper balance of these two strategies.

This article presents a quantitative but simple pair of guidelines for balancing conservation and solar that takes proper account of the solar and weather characteristics of each location. The guidelines do not substitute for thermal evaluation later in the design process, but they do provide a reasonable starting point for schematic design. They are applicable to residential buildings and small commercial buildings having residential levels of internal gains (30-60 Btu/ft^2 per day) (4-8 W/m^2). The two guidelines will be presented first, followed by an example of their use; an explanation of their development is given in the Appendix.

GUIDELINE 1. CONSERVATION LEVELS

Recommended levels of insulation and building airtightness can be computed based on a *conservation factor* (CF). Two suggested levels of CF, corresponding to two different projected fuel costs, are given in Table 1 for 90 U.S. cities. Unless conditions indicate otherwise, use the CF values corresponding to high fuel cost as a starting point.

Use the following formulas to compute guidance values for insulation and airtightness levels.

$$
\begin{aligned}
R_{wall} &= 14 \cdot CF \\
R_{ceiling} &= 22 \cdot CF \\
R_{perimeter} &= 13 \cdot CF - 5 \\
R_{basement} &= 16 \cdot CF - 8 \\
N_{E,W,N} &= 1.7 \cdot CF \\
ACH &= 0.42/CF
\end{aligned}
$$

Based on guidance resulting from these formulas, select practical, buildable conservation levels as a starting point for the design, trying for the most part to stay within 20% of the guidance. For windows, choose the closest integer value.

R_{wall} and $R_{ceiling}$ are the *overall* R-values (h °F ft^2/Btu) of the opaque wall and ceiling insulation, accounting for the series effect of all air layers and materials, including the attic air space, if any.

$R_{perimeter}$, which refers to slab-on-grade construction, is the R-value of insulation *added to* the outside of foundation walls or under the slab perimeter. Normally this is rigid insulation installed below grade against foundation walls down to the footings or 2 ft (0.6 m) wide under the slab. For a floor built over a crawl space, use either the floor-insulation R-value for the frame floor or the perimeter-insulation value outside the stem wall down to the footings.

$R_{basement}$ refers to a heated basement and is the R-value of the insulation outside the exterior basement walls extending 4 ft (1.2 m) below grade. Use 1/2 this R-value from 4 ft (1.2 m) below grade down to the top of the basement-wall footings. Use this same strategy for fully bermed walls.

$N_{E,W,N}$ refers to the number of window glazings to be used on east, west, and north windows. However, if this number exceeds 2, consider using either double glazing combined with movable insulation

Table 1. Guideline Values of Conservation Factor, Load Collector Ratio, and Solar Savings Fraction

	Low Fuel Cost			High Fuel Cost		
	CF	LCR	SSF(%)	CF	LCR	SSF(%)
Birmingham, Alabama	.95	117	31	1.19	41	58
Phoenix, Arizona	.70	123	53	.83	66	74
Winslow, Arizona	1.13	46	57	1.35	25	75
Little Rock, Arkansas	1.04	97	31	1.30	34	59
Fresno, California	.91	108	39	1.12	47	60
Los Angeles, California	.70	96	70	.81	61	84
Red Bluff, California	.92	116	34	1.14	47	58
Sacramento, California	.93	102	40	1.15	46	60
San Francisco, California	.89	70	64	1.04	42	78
Colorado Springs, Colorado	1.30	33	60	1.55	18	78
Denver, Colorado	1.27	36	57	1.52	19	76
Grand Junction, Colorado	1.27	45	47	1.56	21	69
Hartford, Connecticut	1.42	137	13	1.88	36	29
Wilmington, Delaware	1.25	90	23	1.62	28	47
Washington, DC	1.26	97	21	1.64	30	45
Apalachicola, Florida	.69	173	39	.82	74	65
Orlando, Florida	.50	272	46	.59	134	70
Atlanta, Georgia	1.00	101	32	1.24	37	59
Boise, Idaho	1.31	64	33	1.67	28	51
Chicago, Illinois	1.39	121	15	1.83	34	32
Springfield, Illinois	1.32	98	19	1.73	28	42
Evansville, Indiana	1.21	121	19	1.58	34	42
Indianapolis, Indiana	1.33	158	12	1.76	40	30
Burlington, Iowa	1.39	91	19	1.82	27	41
Mason City, Iowa	1.56	81	18	2.07	25	36
Dodge City, Kansas	1.21	49	45	1.49	22	69
Lexington, Kentucky	1.23	131	17	1.60	35	39
Lake Charles, Louisiana	.72	219	28	.89	73	57
New Orleans, Louisiana	.70	176	36	.85	71	64
Caribou, Maine	1.72	92	14	2.29	33	25
Portland, Maine	1.52	103	15	2.02	32	30
Baltimore, Maryland	1.23	92	24	1.58	29	48
Boston, Massachusetts	1.33	113	17	1.75	32	37
Detroit, Michigan	1.40	168	11	1.85	47	24
Traverse City, Michigan	1.54	191	8	2.04	63	16
Int. Falls, Minnesota	1.80	148	8	2.39	59	14
Minneapolis, Minnesota	1.60	126	11	2.13	39	23
Jackson, Mississippi	.86	133	32	1.06	48	60
Columbia, Missouri	1.26	97	21	1.64	28	46
Kansas City, Missouri	1.29	80	25	1.67	25	50
Saint Louis, Missouri	1.22	97	23	1.58	29	48
Billings, Montana	1.47	57	29	1.91	22	48
Dillon, Montana	1.55	41	37	1.98	18	55
Great Falls, Montana	1.51	64	25	1.97	26	41
Omaha, Nebraska	1.43	72	23	1.87	22	47

Table 1. **Guideline Values of Conservation Factor, Load Collector Ratio, and Solar Savings Fraction** (Concluded)

	Low Fuel Cost			High Fuel Cost		
	CF	LCR	SSF(%)	CF	LCR	SSF(%)
North Platte, Nebraska	1.41	44	39	1.77	18	62
Ely, Nevada	1.41	30	59	1.70	16	76
Las Vegas, Nevada	.86	80	55	1.02	43	75
Reno, Nevada	1.23	38	60	1.47	21	77
Concord, New Hampshire	1.51	123	12	2.01	36	27
Newark, New Jersey	1.27	99	21	1.65	29	44
Albuquerque, New Mexico	1.08	48	58	1.29	26	77
Los Alamos, New Mexico	1.29	33	61	1.53	18	79
Albany, New York	1.47	160	10	1.95	42	24
Binghamton, New York	1.50	269	6	1.99	70	15
Buffalo, New York	1.47	261	7	1.94	70	15
New York (Central)	1.25	146	15	1.64	37	36
Asheville, North Carolina	1.14	67	38	1.42	27	63
Raleigh, North Carolina	1.06	88	33	1.32	33	59
Bismarck, North Dakota	1.67	82	16	2.22	29	29
Cleveland, Ohio	1.39	231	8	1.84	62	19
Columbus, Ohio	1.34	184	11	1.78	46	26
Oklahoma City, Oklahoma	1.07	77	37	1.33	30	64
Medford, Oregon	1.22	90	27	1.56	38	43
North Bend, Oregon	1.11	55	53	1.35	29	69
Portland, Oregon	1.21	120	21	1.55	46	36
Philadelphia, Pennsylvania	1.25	103	20	1.62	30	44
Pittsburgh, Pennsylvania	1.37	208	9	1.81	54	22
Providence, Rhode Island	1.37	92	19	1.79	28	40
Charleston, South Carolina	.84	129	35	1.03	51	62
Rapid City, South Dakota	1.48	52	31	1.90	20	52
Sioux Falls, South Dakota	1.56	83	18	2.07	26	35
Memphis, Tennessee	1.02	117	27	1.29	37	55
Nashville, Tennessee	1.10	147	18	1.42	39	44
Amarillo, Texas	1.08	52	54	1.30	26	75
Corpus Christi, Texas	.58	260	35	.70	108	62
Dallas, Texas	.87	118	35	1.06	46	63
El Paso, Texas	.88	74	58	1.04	40	77
San Angelo, Texas	.84	103	44	1.01	47	69
Bryce Canyon, Utah	1.49	24	65	1.77	14	80
Salt Lake City, Utah	1.31	50	41	1.64	22	61
Burlington, Vermont	1.56	229	7	2.08	64	15
Norfolk, Virginia	1.05	85	34	1.31	33	60
Roanoke, Virginia	1.16	78	31	1.47	28	57
Seattle, Washington	1.25	112	22	1.60	48	35
Spokane, Washington	1.44	109	17	1.88	44	28
Charleston, West Virginia	1.21	169	14	1.58	42	34
Green Bay, Wisconsin	1.58	110	13	2.10	37	25
Madison, Wisconsin	1.55	95	16	2.05	30	31
Casper, Wyoming	1.44	34	50	1.78	16	70

or using a low-emittance glazing with U-value less than 0.3 Btu/h °F ft^2 (1.7 W/°C m^2).

ACH refers to the *effective* air changes per hour resulting from natural infiltration and forced ventilation. ACH is the sum of the natural infiltration and the non-heat-recovered portion of the forced ventilation. If a heat-recovery unit is used for forced ventilation, the non-heat-recovered portion is equal to

$$(1 - \text{heat-recovery effectiveness factor}) \cdot ACH_{forced} \cdot$$

If the guidance value is less than ACH = 0.5 air changes per hour, forced ventilation is required to guarantee adequate indoor air quality. For commercial applications or situations with unusually high sources of indoor air pollution, higher ventilation levels may be necessary.

GUIDELINE 2. PASSIVE SOLAR GLAZING AREA

The primary solar parameter of the building is the load collector ratio, LCR, which is defined as follows:

$$LCR = NLC/A_p ,$$

where NLC is the net load coefficient, excluding losses through the solar wall (Btu/°F day), and A_p is the projected area of the solar wall glazing (ft^2). See Balcomb et al. (1982 and 1984) and Jones, Balcomb, et al. (1982), for more complete definitions of these terms. [NLC is the same as BLC in Jones, Balcomb et al. (1982)].

Recommended values of LCR are given in Table 1; however, to use these values to obtain an estimate of A_p, an estimate of NLC must somehow be obtained. NLC depends on the conservation level achieved. If the recommendations of Guideline 1 have been followed, NLC can be estimated approximately as follows:

$$NLC = GF \cdot A_f/CF ,$$

where GF is a geometry factor that accounts for the relative dimensions of the building and A_f is the gross floor area. Suggested values of GF are given in Table 2. Alternatively, GF can be estimated using a formula in the Appendix.

The projected area A_p can now be determined as follows:

$$A_p = NLC/LCR \ .$$

As a starting point for design, the combined projected area of all passive systems should be within 20% of this value. The recommendation is independent of the choice of passive system type or types.

BACKUP HEAT

At this point, a very rough estimate of annual auxiliary heat can be obtained from the relation

$$Q_{aux} = DD \cdot NLC \cdot (1 - SSF) \ .$$

SSF values will depend on system type. Values of SSF for reference design SSD1, a semienclosed sunspace with 50° sloped glazing [see Balcomb et al. (1984) or Jones, Balcomb et al. (1982)] are given in Table 1. For other passive system types, refer to the LCR tables in Appendix 1 of Balcomb et al. (1984).

Table 2. Geometry Factor, GF

Floor Area		Number of Stories			
ft^2	m^2	1	2	3	4
1000	93	7.3			
1500	140	6.5	6.7		
3000	280	5.4	5.4	5.7	
5000	465	4.9	4.7	4.9	5.1
10000	930	4.3	4.0	4.0	4.2
20000	1860	3.9	3.5	3.5	3.5

EXAMPLE

Determine conservation and solar guidelines for a 1175 ft^2 (109 m^2) house in Dodge City, Kansas. Table 1 values, using high fuel cost, are

$$\begin{aligned} \text{CF} &= 1.49 \\ \text{LCR} &= 22 \\ \text{SSF} &= 0.69. \end{aligned}$$

Therefore, guidance values are as follows:

		Recommended Range
R_{wall}	$= 14 \times 1.49 = 21$	17 to 25
R_{ceiling}	$= 22 \times 1.49 = 33$	27 to 40
$R_{\text{perimeter}}$	$= 13 \times 1.49 - 5 = 14$	11 to 17
R_{basement}	$= 16 \times 1.49 - 8 = 16$	13 to 19
$N_{\text{E,W,N}}$	$= 1.7 \times 1.49 = 2.5$	2 or 3
ACH	$= 0.42/1.49 = 0.28$	0.22 to 0.34

From Table 2, for a 1175 ft^2 (109 m^2), single-story building,

$$\text{GF} = 7.0 \; .$$

Therefore, if the conservation guidance is followed,

$$\text{NLC} = 7.0 \times 1175/1.49 = 5520 \text{ Btu/°F day } (2.91 \text{ kWh/°C day}).$$

$$A_p = 5520/22 = 250 \text{ ft}^2 \; (23 \text{ m}^2).$$

For Dodge City, the degree days [base 65°F (18°C)] are 5053°F day (2807 °C day). Therefore,

$$Q_{\text{aux}} = 5053 \times 5520 \times (1 - 0.69) = 8.65 \text{ MBtu/yr } (2530 \text{ kWh/yr}).^*$$

---

*M = 10^6

All these estimates, of course, are subject to updating as the design proceeds. However, they do give valuable guidance for beginning the design.

MAPS

Maps of CF, LCR, and SSF (for a semienclosed sunspace) based on values at 219 locations are given in Figures 1-3.

The ratio of passive solar projected area to building floor area, A_p/A_f, is given by the expression GF/(CF · LCR). This is plotted for a value of GF = 5.49 in Figure 4. Note that normal levels of south glazing are indicated in the cloudier parts of the United States but that larger values, up to 22% of the floor area, are indicated in the sunny and cold intermountain west. Such large values would normally require the use of an indirect passive system in addition to direct gain.

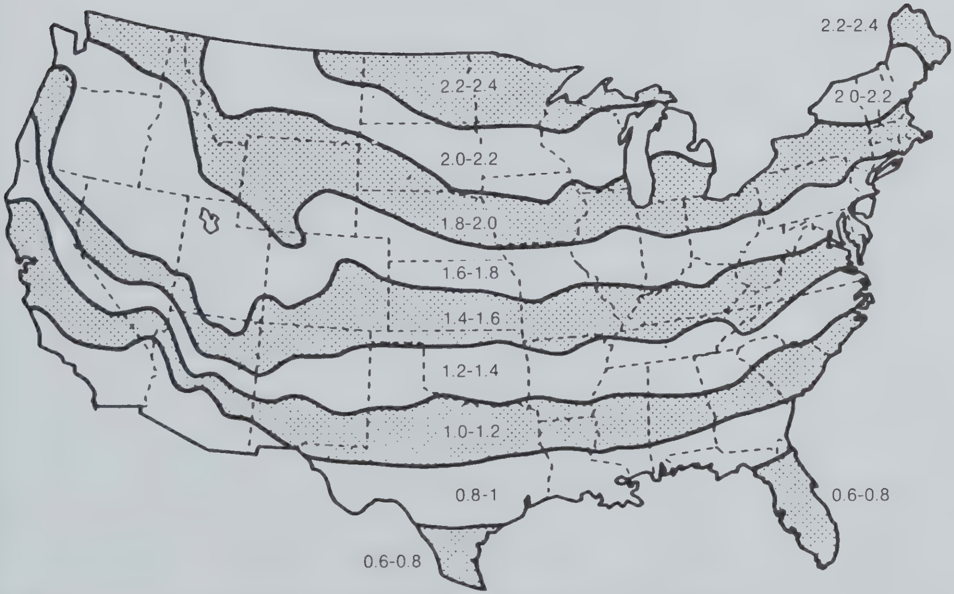


Figure 1. Guideline values of the conservation factor (CF)

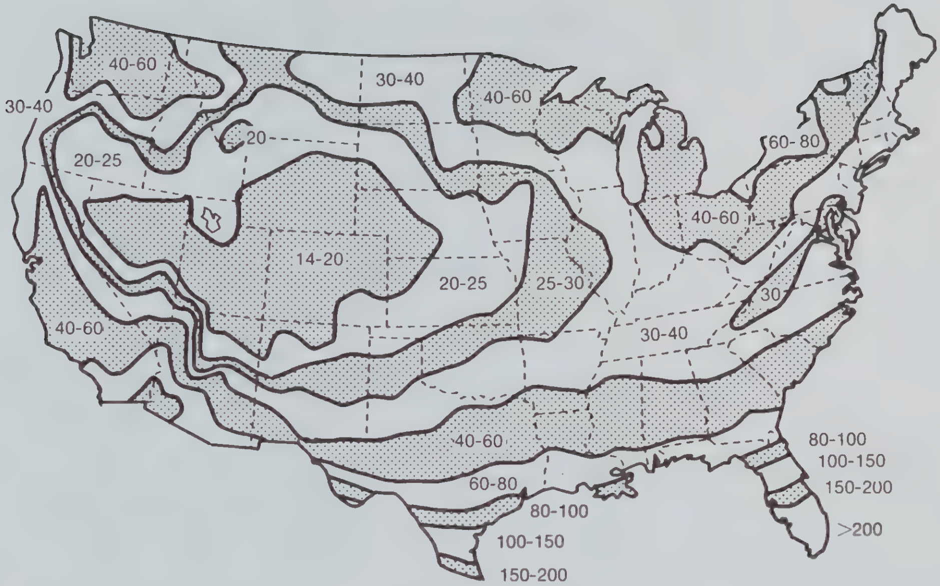


Figure 2. Guideline values of the load collector ratio (LCR), Btu/°F day ft^2

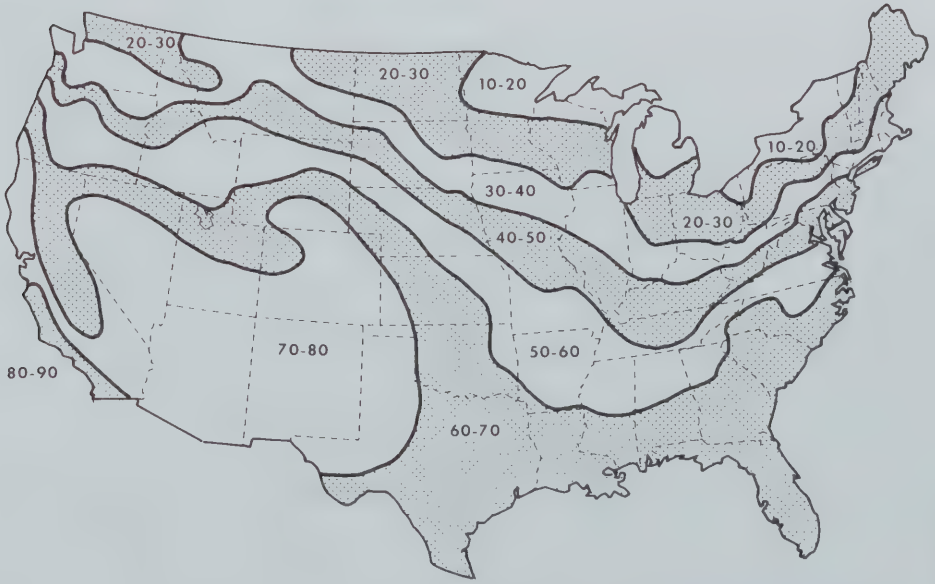


Figure 3. Solar savings fractions (%) for the guideline values of LCR for a semienclosed sunspace with 50° sloped glazing (reference design SSD1)

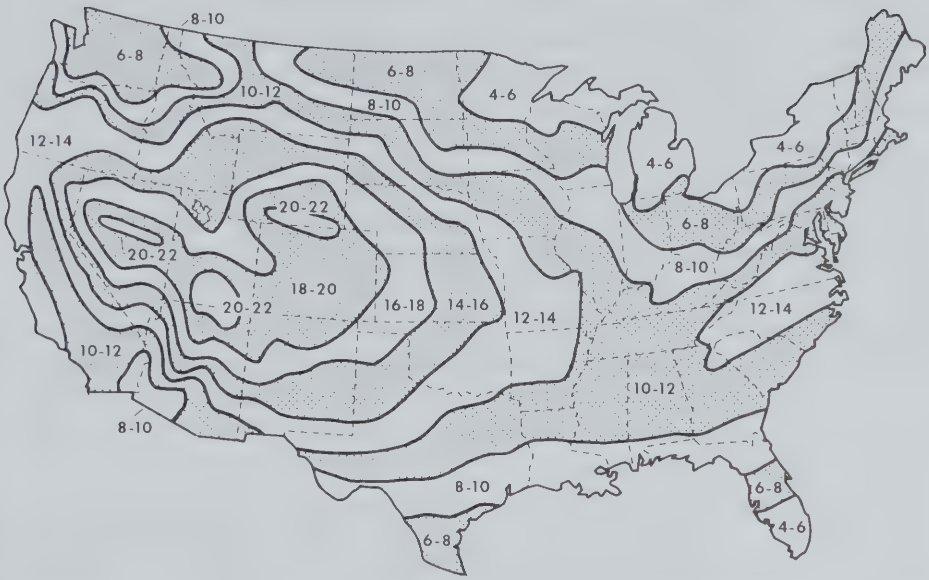


Figure 4. Ratio of solar projected area to building floor area (%) corresponding to Figures 1 and 2 and GF = 5.49

BASIS FOR THE GUIDELINES

Table 1 has been developed based on balancing the incremental cost/benefit of conservation and solar strategies using sunspace system SSD1. Each case in Table 1 represents an economic life-cycle cost optimum for each city for identical assumed fuel costs and financial parameters. Thus, the table shows how the optimum mix of conservation and solar varies with climate.

To obtain simple guidelines, assumed values have been used for the incremental cost of passive solar aperture, conservation improvements, and fuel; the escalation rate of fuel; and the fixed charge rate. These are outlined in the Appendix, which explains how to modify the guidelines to account for any desired set of assumed costs. Note, however, that the guidelines depend on cost ratios and thus will not change with inflation if all costs escalate proportionally. The "high fuel cost" column in Table 1 is intended to represent the cost of electric resistance heat in much of the United States (about 6.5¢/kWh in 1983 dollars); the "low fuel cost" column is based on one-half the high fuel cost.

The choice of LCR for a guideline means that this single parameter can be used throughout the entire United States for all suitable passive-system types. The LCR values that are obtained for the high fuel cost case are reasonably close to the overheating limit in U.S. cities where winter overheating might be a problem, and are close to buildable limits in cold, sunny climates. Thus, the life-cycle cost criteria used in developing Table 1 are reasonably compatible with other criteria that might have been used instead.

The formula for NLC is based on the premise that conservation levels will be set based on the conservation guidelines. If different conservation levels are used, A_p should be based on a realistic estimate of NLC and the recommended value of LCR.

The guidelines are based on heating-season performance only. Nevertheless, summer cooling should also be a major concern of the designer, especially in the hotter areas of the nation. The first strategy should always be a good defense. This consists primarily of avoiding solar gains in the summer through effective window placement and shading. Deciduous trees are particularly effective to the east and west of the building but should not be used in the south 120° sector. Various passive cooling strategies can also be used. Most importantly, care should be taken to insure that the passive heating system does not exacerbate the cooling load. Full shading may be warranted in some areas; several studies have indicated that unless this is done, diffuse solar gains alone will add significantly to the cooling load. Results from studies by McFarland at Los Alamos indicate that Trombe walls and water walls result in the least cooling load, sunspaces are next (depending on glazing slope), and direct gain usually results in the greatest cooling load. Sloped glazing should probably be avoided (or well shaded in the summer) on sunspaces in the warmest climates. East and west sunspace glazing should be minimized in all locations, and adequate summer venting should be provided. A method of accounting for cooling loads added due to the passive solar aperture is discussed in the Appendix.

Comments Regarding Passive System Selection

The rationale for choosing the semienclosed sunspace system SSD1 for developing Table 1 is based on observing the nature of the results. The results for other systems lie reasonably close to the SSD1 results if appropriate system costs are used and if the system is used only in suitable regions; for example, direct gain with night insulation in cold climates and direct gain without night insulation in warmer climates.

The double-glazed, semienclosed sunspace system SSD1 is a good performer throughout U.S. climates without requiring night insulation (although performance is considerably improved with night insulation). Whereas we wanted to avoid requiring night insulation in developing a general guideline, night insulation (or a selective surface on a water wall or Trombe wall) may well be advisable in cold climates.

Base-Temperature Calculation

The base temperature used for calculating degree-days needed to develop Table 1 was adjusted over a range of approximately 56°F (13°C) (in Minnesota) to 67°F (19°C) (in Florida) to account for internal heat generation and a thermostat setpoint of 70°F (21°C). The internal heat rate assumed is 47 Btu/day ft^2 (6.2 W/m^2) of floor area, as might be associated with a residential application.

PASSIVE SYSTEM PERFORMANCE

Normally the selection of a passive system type or types will be dictated by the architectural program. Some direct gain is usually incorporated in the design, but the window area should be determined primarily by the need for view and daylight. Certainly the amount of direct gain should be limited by the effective thermal storage mass available to avoid large temperature swings. If the guidelines call for more passive solar area than can be accommodated using direct gain, then an indirect system or systems should be used for the remainder. Unvented Trombe walls are particularly effective in this case because the delivery of solar heat is out of phase with daytime direct gain; however, other indirect systems such as sunspaces are also effective. Sunspaces are often chosen because the room created is useful and desired as a greenhouse, entry, or traffic area; and the solar heating then becomes an added benefit. It would normally be difficult to justify a sunspace economically without such dual use.

To a lesser extent, system performance may also serve as a basis for selection of passive system types. However, within any passive type, performance varies widely. For example, direct gain is a poor performer in cold climates, but direct gain with night insulation competes with the best of the other system options. The purpose of this section is to indicate general performance trends for a few systems to show how solar savings changes with location and system type.

In Figures 5 through 11, system performance is given in terms of the annual solar savings (Btu) per square foot of projected area. This is obtained from the equation

$$\text{solar savings} = \text{SSF} \cdot \text{LCR} \cdot \text{DD},$$

where DD is computed for an appropriate base temperature as described above.

Direct-gain savings are shown in Figure 5. The additional savings attributed to adding R-9 night insulation to direct gain are shown in Figure 6. Similarly, Figure 7 shows sunspace savings and Figure 8 shows additional savings attributed to night insulation. Trombe wall savings are shown in Figure 9, and the added savings associated with use of a selective surface on a Trombe wall are shown in Figure 10. Note that the system in Figure 9 is double glazed, and in Figure 10 it is single glazed. Figure 11 shows solar savings of a water wall with single glazing and selective surface. The particular reference systems are identified on each figure. These refer to the system designations given in Balcomb et al. (1982 and 1984) and Jones, Balcomb et al. (1982). The savings of any of the other 94 systems that have been correlated can be calculated using the value of SSF determined from the LCR tables in Jones, Balcomb et al. (1982), Balcomb et al. (1984), or by using the appropriate solar load ratio correlation.

Annual auxiliary heat required for a 1175 ft^2 (109 m^2) house is shown in Figure 12. Figure 13 shows the annual savings for this house compared with conventional construction; this is the combined

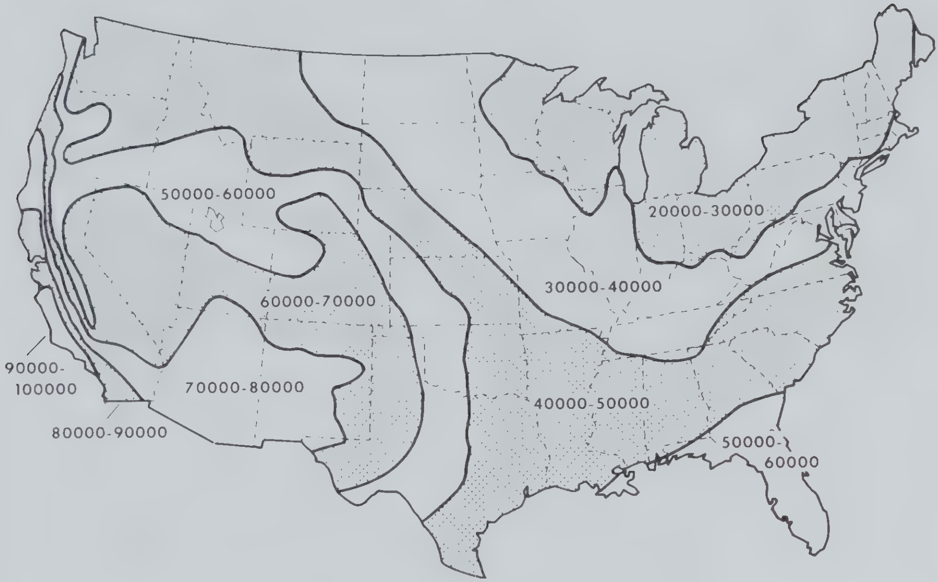


Figure 5. Annual solar savings for direct-gain DGC1, Btu/ft^2 of projected area. Heat storage is 4-in. (10-cm) concrete with a mass-surface-to-glass-surface area ratio of 6.

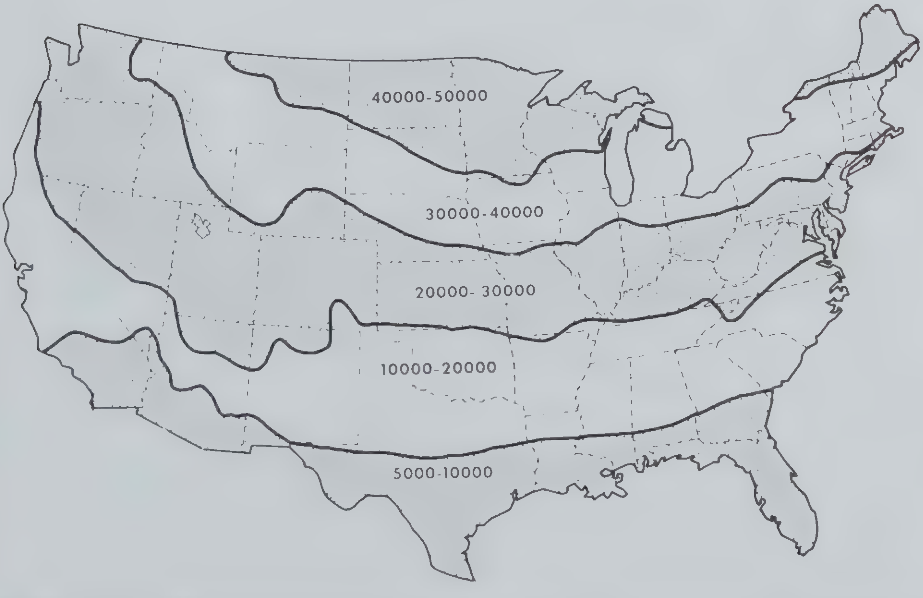


Figure 6. Added annual solar savings as a result of adding R-9 night insulation to the direct-gain system of Figure 5 (system DGC3 vs DGC1), Btu/ft^2 of projected area

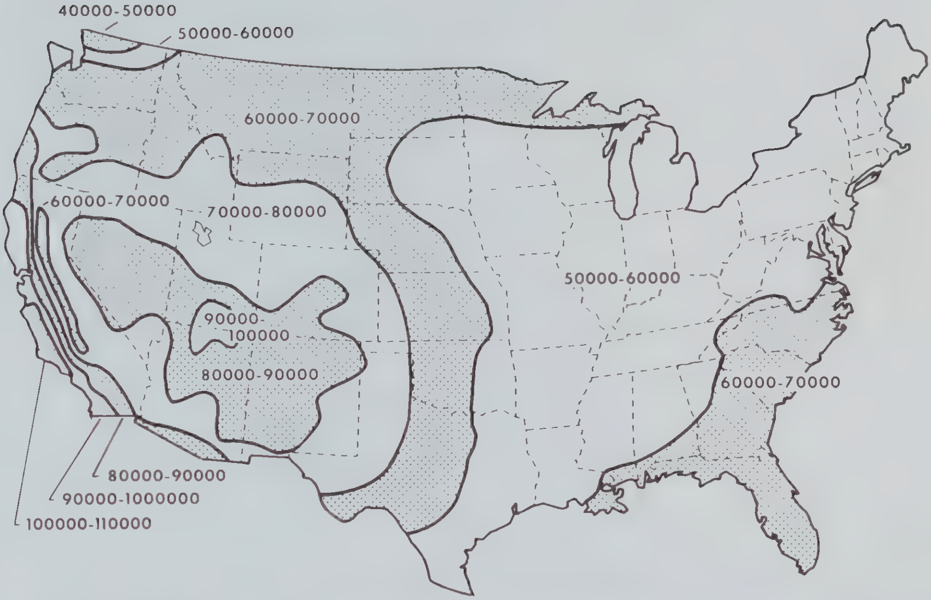


Figure 7. Annual solar savings for semienclosed sunspace system SSD1 with 50° sloped glazing, Btu/ft^2 of projected area

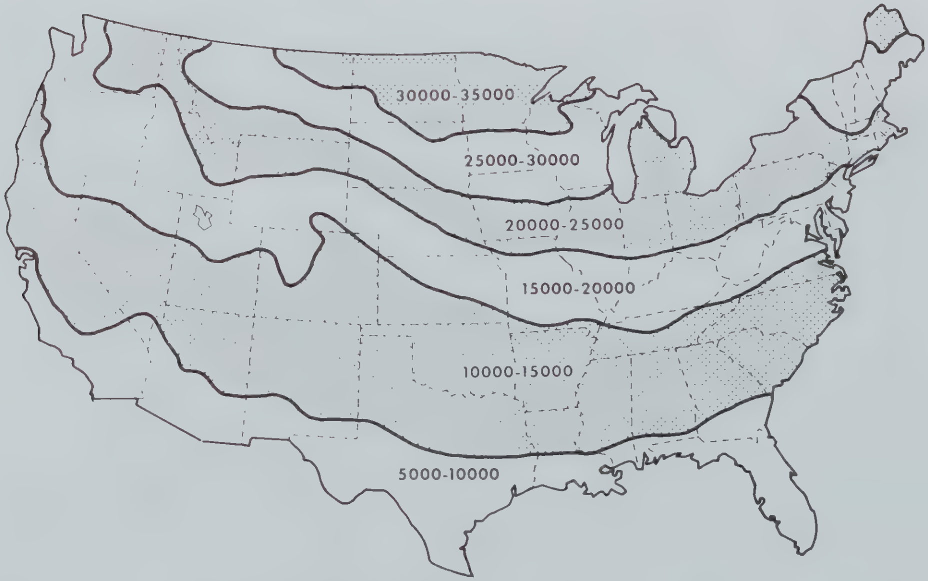


Figure 8. Added annual solar savings as a result of adding R-9 night insulation to the sunspace of system in Figure 7 (system SSD2 vs SSD1), Btu/ft^2 of projected area

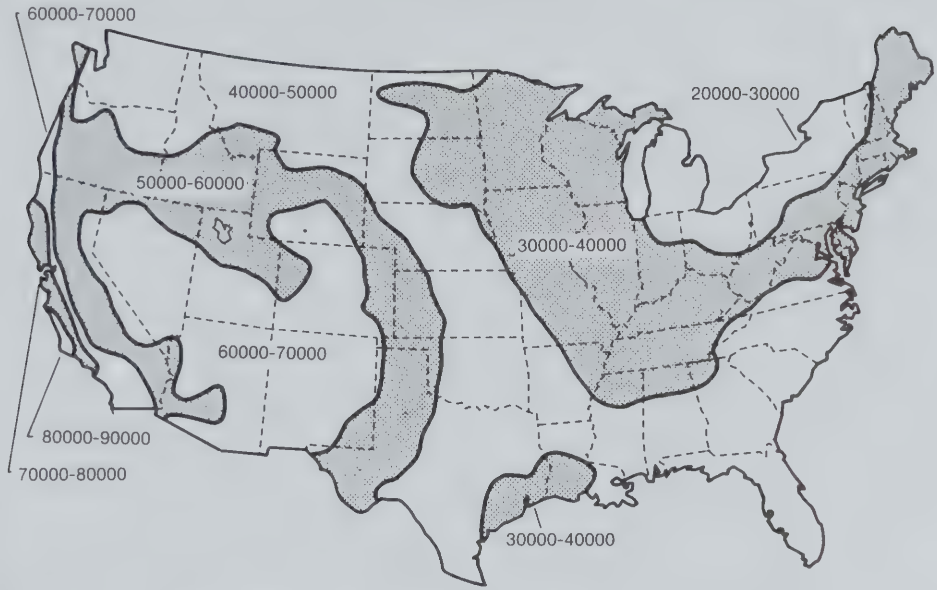


Figure 9. Annual solar savings for the unvented, double-glazed, flat-black Trombe wall system TWF3, Btu/ft^2 of projected area

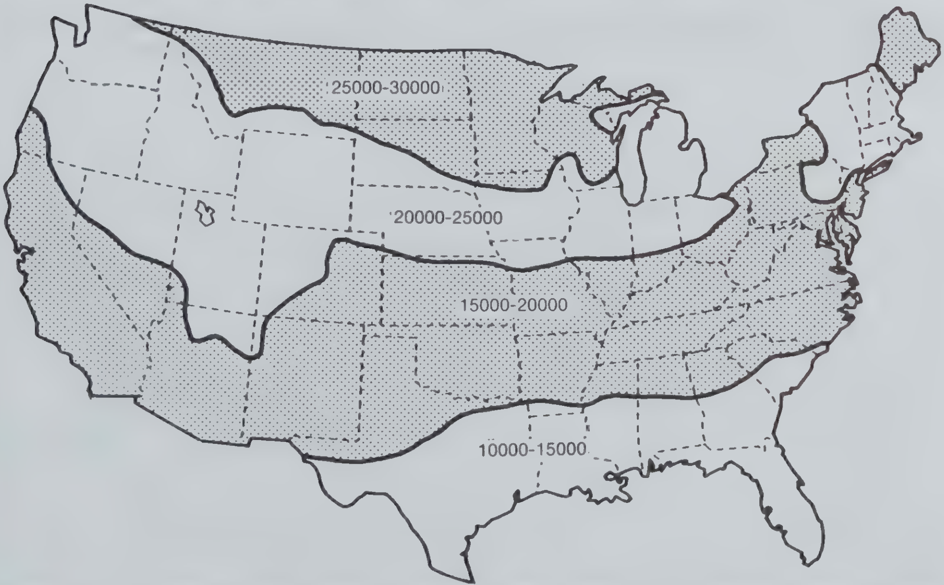


Figure 10. Added annual solar savings as a result of removing one glazing from the Trombe wall system of Figure 9 and then adhering a selective surface (emittance = 0.1) on the exterior face of the Trombe wall to reduce radiation losses (system TWJ1 vs TWF3), Btu/ft^2 of projected area. The contours of added solar savings as as result of adding night insulation to the Trombe wall system of Figure 9 are nearly identical to these contours (system TWI4 vs TWF3).

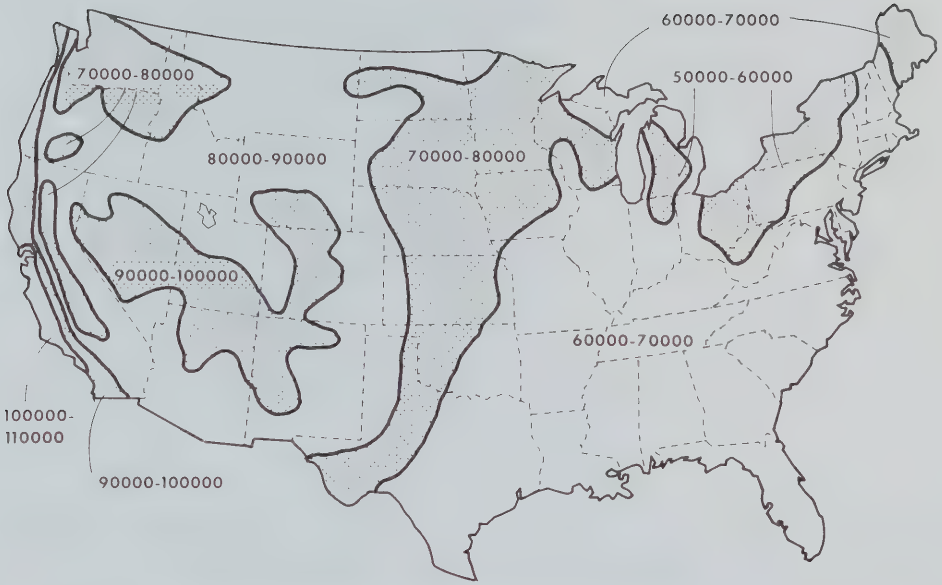


Figure 11. Annual solar savings for water wall system WWC1, which has single glazing and a selective surface, Btu/ft^2 of projected area

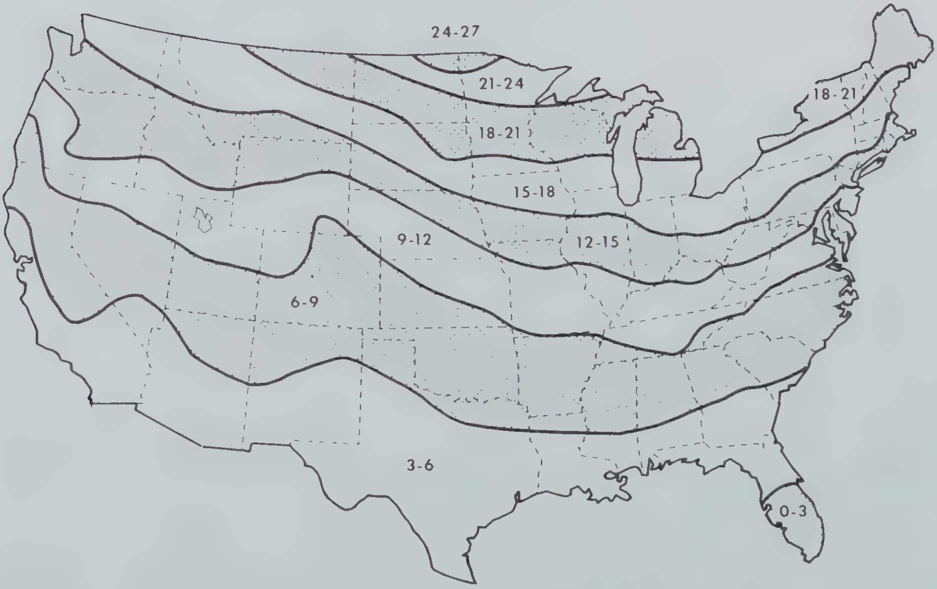


Figure 12. Annual auxiliary heat (MBtu) for a 1175 ft^2 (109 m^2) building using sunspace system SSD1. This combines the conservation factors of Figure 1 with the load collector ratio of Figure 2 and the solar savings fraction of Figure 3. The geometry factor GF is 7.0 so that the net load coefficient NLC = 8225/CF.

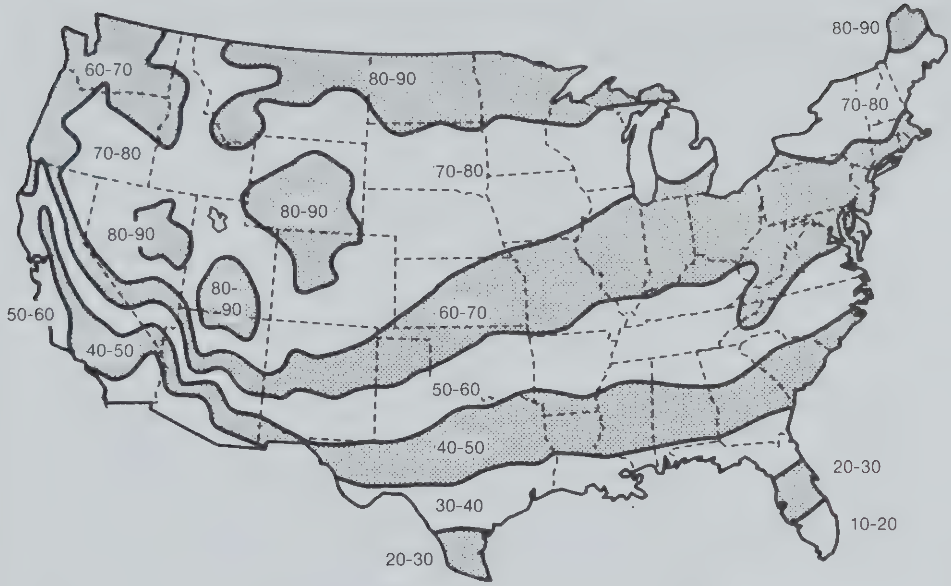


Figure 13. Annual savings (MBtu), due to conservation and solar combined, for the 1175 ft^2 (109 m^2) house of Figure 12 compared with a nonsolar house of conventional construction

savings due to both conservation and solar. For this map, the base-case annual heat for conventional construction is obtained using a 65°F (18°C) base temperature for the calculation of degree days and a load coefficient of (MBtu/°F day)

$$LC = 1.065/\sqrt{DD}\ ,$$

where DD is the annual Fahrenheit heating degree-days (base 65°F).

This follows directly from the assumption that conventional construction has gradually been optimized over the years for a fuel cost of \$2.00/MBtu (assuming 66% fuel-conversion efficiency to heat) and the conservation costs given in the Appendix. The corresponding value of wall insulation is

$$R_{wall} = 0.11\sqrt{DD}\ ,$$

which is in reasonable agreement with past practice. Although the base-case assumption in Figure 13 is fairly crude, it does give an indication that enormous energy savings can be achieved using the combined conservation and solar strategy. In any case, the auxiliary heat requirement shown in Figure 12 is independent of the base case and is very low compared with conventional construction. Figure 14 shows the wall R-value obtained using the guideline values.

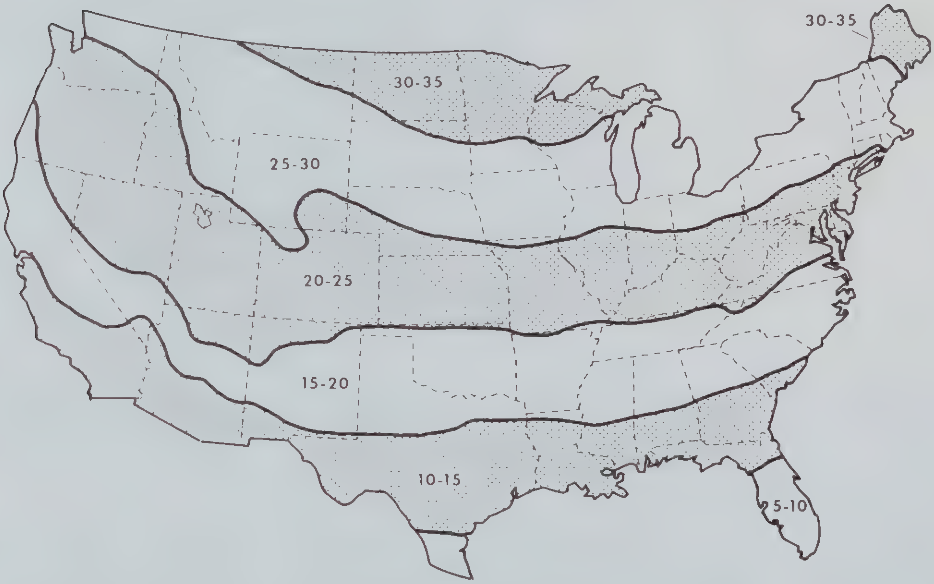


Figure 14. Guideline wall R-values obtained using $R_{wall} = 14 \cdot CF$

APPENDIX

Cost Equations

Minimum life-cycle cost is the criterion used to determine guideline values for each city. Life-cycle cost LCC is given by the formula

$$\text{LCC} = \text{system cost} + \text{fuel cost}. \quad (1)$$

Because each of these costs must be expressed in common terms, initial cost is used as common basis.

The system first cost is made up of portions ascribable to conservation and solar add-on costs; system cost = $C_s + C_c$. The solar first cost C_s is assumed to scale directly with system projected area:

$$C_s = a\,A_p, \tag{2}$$

where a is the incremental passive system cost per unit of projected area.

The conservation first cost C_c is assumed to depend inversely on the net load coefficient NLC as follows:

$$C_c = b/\mathrm{NLC} - C_1\,, \tag{3}$$

where b and C_1 are constants. The reasonableness of this equation for the situation of discrete choices of conservation levels is discussed in Balcomb (1980).

The initial annual fuel cost is given by the formula:

$$\text{Fuel cost (first year)} = \mathrm{CH} \cdot Q_{aux}, \tag{4}$$

where Q_{aux} is the annual backup heat required, and CH is the current cost of heat delivered into the building.

The annual backup heat is given by the formula:

$$Q_{aux} = \mathrm{NLC} \cdot \mathrm{DD} \cdot (1 - \mathrm{SSF}), \tag{5}$$

where DD is the annual heating degree-days. Contours of constant Q_{aux}, with C_c and C_s as axes, are shown for Dodge City, Kansas, in Figure 15.

To put future fuel costs in terms of an equivalent initial cost so that they may be fairly compared with system costs, a levelization factor FF and fixed charge rate FCR are used. The present value of the sum of all future fuel costs is given by

$$\text{Fuel cost (present value)} = \mathrm{CH} \cdot Q_{aux} \cdot \mathrm{FF}/\mathrm{FCR}. \tag{6}$$

The fixed charge rate FCR converts an initial cost to an equivalent annual cost. It should include not only direct effects such as interest on a mortgage, discount rate, and tax credits, but indirect effects stemming from deductions on interest payments, increased resale value of the solar system, property tax rates, reduced size of the backup heating system, and maintenance costs.

The levelization factor FF converts a current annual cost of heat into an equivalent annualized cost, accounting for the future cost of fuel (or electricity) and the discount rate. The current cost of heat should account for the

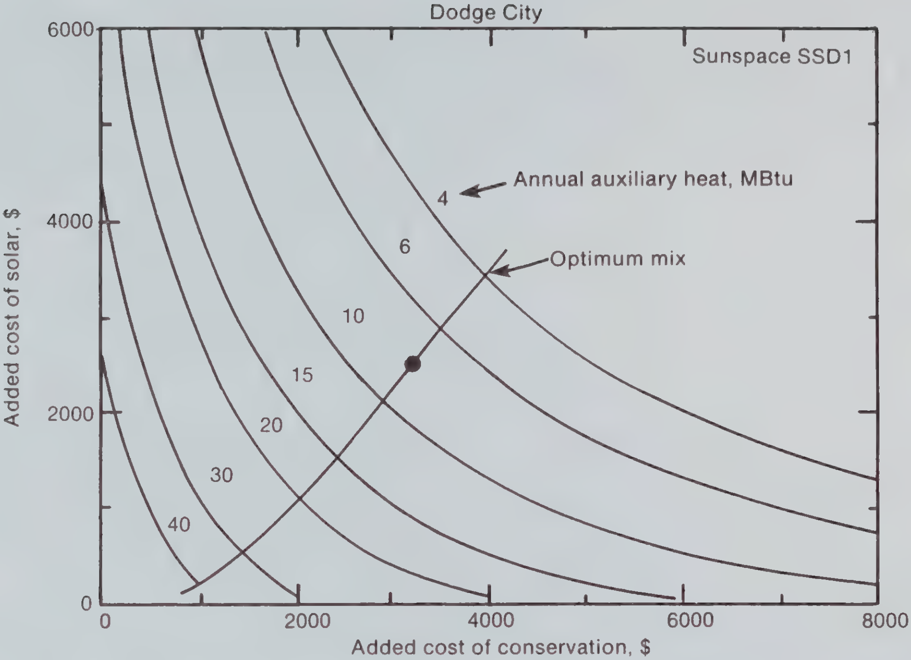


Figure 15. Cost/performance map for Dodge City using assumed costs. The reference case (no added solar or conservation costs) is a 1175 ft^2 (109 m^2) building with NLC = 15,000 Btu/°F day and $A_p = 0$. The line labeled "Optimum mix" results in minimum annual auxiliary heat for any given initial investment.

efficiency of the backup heater in converting fuel (or electricity) into useful delivered heat. See Balcomb et al. (1980) for a discussion of fixed charge rate and levelization factor.

The life-cycle cost LCC in present-value terms, is the sum of the initial system costs and the present value of the future fuel costs, as follows:

$$LCC = a\ A_p + b/NLC - C_1 + h \cdot (1 - SSF) \cdot NLC, \tag{7}$$

where

$$h = (CH \cdot FF \cdot DD)/FCR. \tag{8}$$

Contours of constant LCC, on the same axes as those shown in Figure 15, are shown in Figure 16.

Although not included explicitly in the above discussion, the summer cooling penalty associated with passive solar collection area could be accounted for by increasing the value of a, the incremental cost of passive solar collection area. To do this, one would have to determine the added cooling cost per unit

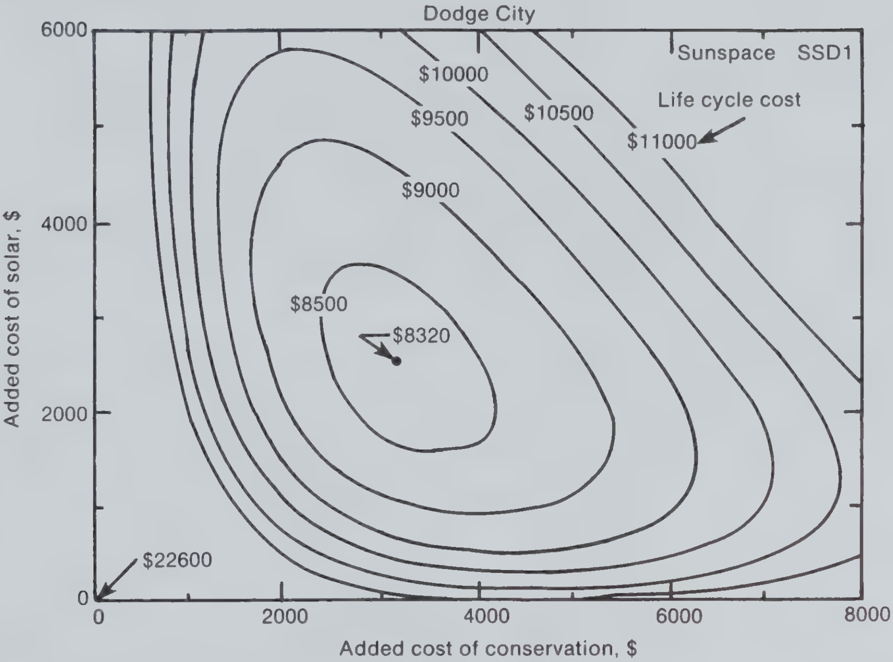


Figure 16. Contours of constant life-cycle cost plotted on the same coordinates as Figure 15. A minimum life-cycle cost is achieved for a \$3240 investment in conservation and a \$2500 investment in passive solar. At this point the life-cycle fuel cost is \$2580, LCR = 22.1 Btu/ft^2 °F day, SSF = 69%, NLC = 5520 Btu/°F day, A_p = 250 ft^2 (23 m^2), auxiliary = 7.7 MBtu/yr, and conservation factor CF = 1.49. Degree days are 4520 for a base temperature of 63°F (2511, base 17°C). This point is also shown plotted on Figure 15.

area of passive aperture. This number can then be converted into a present value by multiplying by FF and dividing by FCR. The result is an equivalent added cost of the passive system that can be incorporated into the value of a.

Optimization

If LCC is minimized (global optimum) independently with respect to A_p and NLC, it follows that the following two equations must be satisfied:

$$D = a/h, \qquad (9)$$

and

$$NLC = \sqrt{\frac{b}{a[1/LCR + (1 - SSF)/D]}}\ , \qquad (10)$$

where

$$D = d(SSF)/d(1/LCR) \qquad (11)$$
(derivative of SSF with respect to 1/LCR).

This is the global optimum shown in Figure 16. The equation for NLC, used alone, balances conservation and solar to minimize annual auxiliary for a fixed initial investment. This is the constrained optimum line labeled "optimum mix" in Figure 15. In either case, the solution is obtained by iteration, beginning with a guess for LCR.

Conservation Formulas

The conservation factor, CF, in Table 1 is defined by the following equation

$$CF = \sqrt{24(1/LCR + (1 - SSF)/D)}\,, \qquad (12)$$

so that

$$NLC^2 = \frac{24b}{h \cdot D \cdot CF^2} = \frac{24b}{a \cdot CF^2}\,. \qquad (13)$$

The net load coefficient NLC is the sum of several independent parts resulting from parallel heat-flow paths from the building inside to outside.

Simple, approximate equations for the main heat-loss paths are given in Balcomb et al. (1980) as follows:

$$\begin{aligned}
NLC = \;& 24 \cdot A_w/R_w && \text{due to walls,} \\
+ \;& 24 \cdot A_c/R_c && \text{due to ceiling,} \\
+ \;& 26 \cdot A_g/N_{E,W,N} && \text{due to E,W,N windows,} \\
+ \;& 100 \cdot L_p/(R_p + 5) && \text{due to foundation perimeter,} \\
+ \;& 256 \cdot L_b/(R_b + 8) && \text{due to basement perimeter,} \\
+ \;& 0.432 \cdot V \cdot ADR \cdot ACH && \text{due to infiltration,} \qquad (14)
\end{aligned}$$

where

A_w = wall opaque area, ft^2,
A_c = ceiling area, ft^2,
A_g = E, W, and N glazing area, ft^2,
L_p = foundation outside-perimeter length, ft (slab-on-grade),
L_b = basement perimeter length, ft,
V = building volume, ft^3, and
ADR = air-density ratio, dimensionless.

The incremental cost of each conservation strategy is given by a value r, as follows:

r_w = cost per R per unit area for wall insulation,
r_c = cost per R per unit area for ceiling insulation,
r_p = cost per R per unit length for perimeter insulation,
r_b = cost per R per unit length for basement insulation,
r_g = cost per glazing per unit area for one extra glazing,
r_i = cost per HAC per unit volume for decreasing infiltration,

where HAC = 1/ACH is the hours per air change.

If these incremental costs are constant, the method of Lagrangian multipliers can be used to identify conservation levels that minimize the conservation add-on cost as follows (see Balcomb, 1980):

Walls: $R_w = CF\sqrt{a/r_w}$,

Ceiling: $R_c = CF\sqrt{a/r_c}$,

Perimeter: $R_p = CF\sqrt{\frac{100\ a}{24\ r_p}} - 5$,

Basement: $R_b = CF\sqrt{\frac{256\ a}{24\ r_b}} - 8$,

Windows:
(E,W,N) $N_{E,W,N} = CF\sqrt{\frac{26\ a}{24\ r_g}}$,

Infiltration: $ACH = \frac{\sqrt{\frac{24\ r_i}{0.432\ a\ ADR^2}}}{CF}$.

These equations are of the same form as the conservation guidelines. The constants in the equations are given by:

Walls: $R_w = CP_w \cdot CF$ $CP_w = \sqrt{a/r_w}$,

Ceiling: $R_c = CP_c \cdot CF$ $CP_c = \sqrt{a/r_c}$,

Basement: $R_b = CP_b \cdot CF - 8$ $CP_b = \sqrt{256\ a/(24\ r_b)}$,

Perimeter: $R_p = CP_p \cdot CF - 5$ $CP_p = \sqrt{100\ a/(24\ r_w)}$,

Windows:
(E,W,N) $N_{E,W,N} = CP_{E,W,N} \cdot CF$ $CP_{E,W,N} = \sqrt{26\ a/(24\ r_g)}$,

Infiltration: $ACH = CP_i/CF$ $CP_i = \sqrt{24\ r_i/(0.432\ a\ ADR^2)}$.

Note that these CP values only depend on cost ratios.

Formula for the Geometry Factor GF

If we substitute the conservation levels into the equation for NLC, we obtain,

$$NLC = 24\,P/(\sqrt{a}\,CF) \tag{15}$$

where

$$P = A_w\sqrt{r_w} + A_c\sqrt{r_c} + L_p\sqrt{(100/24)\,r_p} + L_b\sqrt{(256/24)\,r_b} + A_g\sqrt{(26/24)\,r_g} + V\sqrt{(0.432/24)\,r_i}\,. \tag{16}$$

The geometry factor, GF, is defined so that

$$NLC = GF \cdot A_f/CF\,. \tag{17}$$

Therefore,

$$GF = \frac{24}{\sqrt{a}}\,\frac{P}{A_f}\,. \tag{18}$$

Comparing Equations 13 and 15, we obtain:

$$b = 24\,P^2\,.$$

Cost Assumptions

Table 1 was developed by specifying passive system type SSD1 and then finding values of LCR such that the following values of D would result:

High fuel cost	D = 30,000/DD
Low fuel cost	D = 60,000/DD

where DD is the Fahrenheit heating degree-days.

Because D = a/h = (a · FCR)/(CH · FF · DD), we infer the following ratios:

High fuel cost	(a · FCR)/(CH · FF) = 30,000,
Low fuel cost	(a · FCR)/(CH · FF) = 60,000.

Values for CF, LCR, and SSF in Table 1 correspond to any values of a, FCR, CH, and FF that satisfy these conditions. One particular set of values is as follows:

a = \$10/ft^2 (\$107/m^2)
FCR = 0.1
CH = \$22.22/MBtu (6.5¢/kWh) (high fuel cost)
CH = \$11.11/MBtu (3.25¢/kWh) (low fuel cost)
FF = 1.5

Obviously, many other choices could have been made while continuing to satisfy the equation for D.

The recommended values of CP were obtained by using a = \$10/ft^2 (\$107/m^2) and the following values for r:

Walls	$r_w = 0.05$	\$/R-ft^2
Ceiling	$r_c = 0.03$	\$/R-ft^2
Perimeter	$r_p = 0.25$	\$/R-lineal ft
Basement	$r_b = 0.50$	\$/R-lineal ft
E,W,N Windows	$r_g = 4.00$	\$/glazing
Infiltration	$r_i = 0.0312$	\$/HAC-ft^3

Values of GF were determined from typical building geometry and the cost assumptions given above. For a 1500 ft^2 (140 m^2), one-story building, the following were used:

		Component of P/A_f
Opaque walls	$A_w = 1366$ ft^2 (127 m^2) $r_w = 0.05$	0.204
Ceiling	$A_c = 1500$ ft^2 (140 m^2) $r_c = 0.03$	0.173
Perimeter	$L_p = 165$ ft (50 m) $r_p = 0.25$	0.112
Basement	$L_b = 0$ $r_b = 0.50$	0.000
Windows (E,W,N)	$A_{E,W,N} = 109$ ft^2 (10 m^2) $r_g = 4.00$	0.151
Infiltration	$V = 13500$ ft^3 (382 m^3) $r_i = 0.0312$	0.213
P/A_f		0.853

Therefore, $GF = \frac{24 \times 0.853}{\sqrt{a}} = \frac{20.5}{\sqrt{a}}$;

for a = 10, GF = 6.5.

GF for other buildings was obtained similarly, scaling the dimensions up or down appropriately.

ACKNOWLEDGMENTS

This work was performed under the auspices of the U.S. Department of Energy, Office of Solar Heat Technologies.

REFERENCES

Balcomb, J.D., 1980. Conservation and solar: working together. *Proc. 5th National Passive Solar Conf.* (Amherst, MA, Oct. 19-26, 1980) Newark, DE: AS/ISES, pp. 44-50.

Balcomb, J.D., C.D. Barley, R.D. McFarland, J.E. Perry, Jr., W.O. Wray, and S. Noll, 1980. *Passive Solar Design Handbook, Vol. Two*, DOE/CS-0127/2. Washington, DC: U.S. Department of Energy.

Balcomb, J.D., R.W. Jones, R.D. McFarland, and W.O. Wray, 1982. Expanding the SLR method. *Passive Solar Journal* 1(2):67-90.

Balcomb, J.D., R.W. Jones, R.D. McFarland, and W.O. Wray. 1984. *Passive Solar Heating Analysis*. Atlanta, GA: ASHRAE.

Jones, R.W. (Ed.), J.D. Balcomb, C.E. Kosiewicz, G.S. Lazarus, R.D. McFarland, and W.O. Wray, 1982. *Passive Solar Design Handbook, Vol. Three*. DOE/CS-0127/3. Washington, DC: U.S. Department of Energy.

Passive Solar Journal, 3(3), 249-276 (1986)

The Air-core System for Thermal Storage

Bion D. Howard
National Association of Home Builders
15th and M Streets, NW
Washington, DC 20005

Abstract

The hollow masonry heat storage (HMHS), or "air-core," system for hybrid thermal storage in solar buildings is surveyed. The HMHS system is a remote thermal mass system in which the hollow cores of structural mass such as the cores in concrete blocks are used for warm-air circulation passages. The walls, floors, and ceilings can serve as HMHS elements. Various approaches to HMHS design are reviewed, and four example systems are described. Results are presented from a monitored building with an air-core storage wall.

Copyright © 1986 by Marcel Dekker, Inc.

INTRODUCTION

The concept of storing heat in building masonry for comfort conditioning is not new, but interest in it has renewed in recent years. Much of this resurgence of interest is due to our focus on passive energy systems and ongoing debate on the relative costs, effectiveness, and virtues of lightweight versus massive (masonry and log) construction.

Early passive solar heating systems use the first generation technology of combining glass and mass in insulated, well-sealed envelopes. These systems include direct gain and indirect gain by means of thick mass walls that absorb solar radiation on one side and radiate stored and conducted heat to the living space on the other side. Rock beds appear in a few hybrid projects in which fans circulate passively collected heat through the rocks, but monitored results have not shown them to be particularly effective.

A second generation of hybrid energy systems are the remote thermal mass systems using hollow cores of structural mass such as the concrete block, air-core floor and wall systems, or the Air-Floor, a proprietary patterned metal duct system over which concrete slabs are cast. The relative costs and merits of various under-floor hybrid storage systems are described by Lewis (1982). Figure 1 shows five such generic systems integrated into floors in passive hybrid buildings. Costs range from \$4.00 to \$5.00/ft^2 (\$43.00 to \$54.00/m^2) according to analysis, corrected to current dollars.

A hollow masonry heat storage (HMHS) system can be composed of walls, floors, and even ceilings using various construction materials with inherent duct-like openings such as concrete block, metal decking, ADS tubes, pre-cast concrete decking, double-wythe brick, and even structural clay-tile. Cast-in-place concrete and insulated tilt-up panels can permit airflow inside pre-engineered cavities. Many cost-effective possibilities exist. The overall cost of this form of heat storage can be significantly reduced if it serves a structural as well as a heat storage function.

Robert Mitchell was one of the first to examine analytically the concrete block, air-core system. Mitchell and Giansante (1979) describe an approach for analysis of heat transfer in the system,

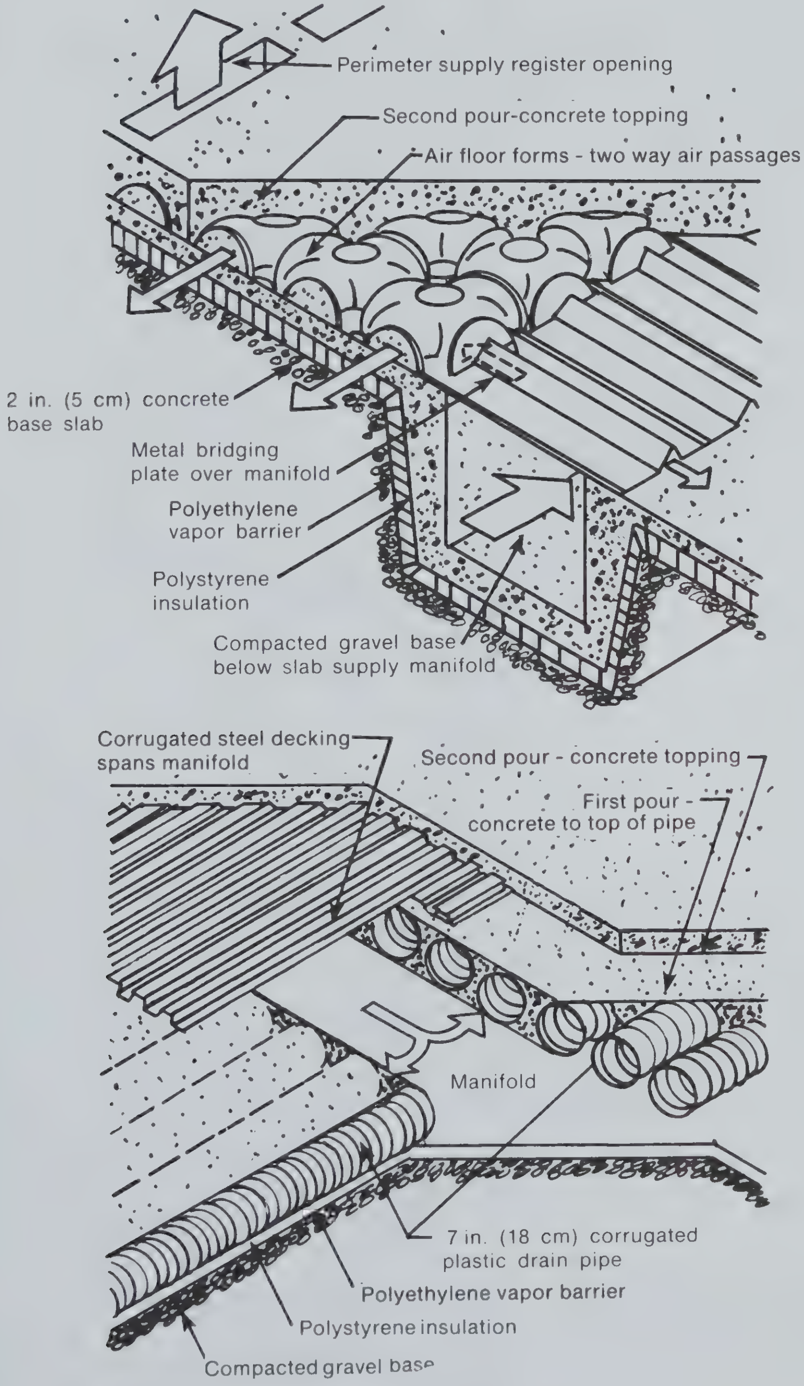

Perimeter supply register opening
Second pour-concrete topping
Air floor forms - two way air passages
2 in. (5 cm) concrete base slab
Metal bridging plate over manifold
Polyethylene vapor barrier
Polystyrene insulation
Compacted gravel base below slab supply manifold
Corrugated steel decking spans manifold
Second pour - concrete topping
First pour - concrete to top of pipe
Manifold
7 in. (18 cm) corrugated plastic drain pipe
Polyethylene vapor barrier
Polystyrene insulation
Compacted gravel base

Figure 1. Five generic air-core floor systems (Lewis, 1982)

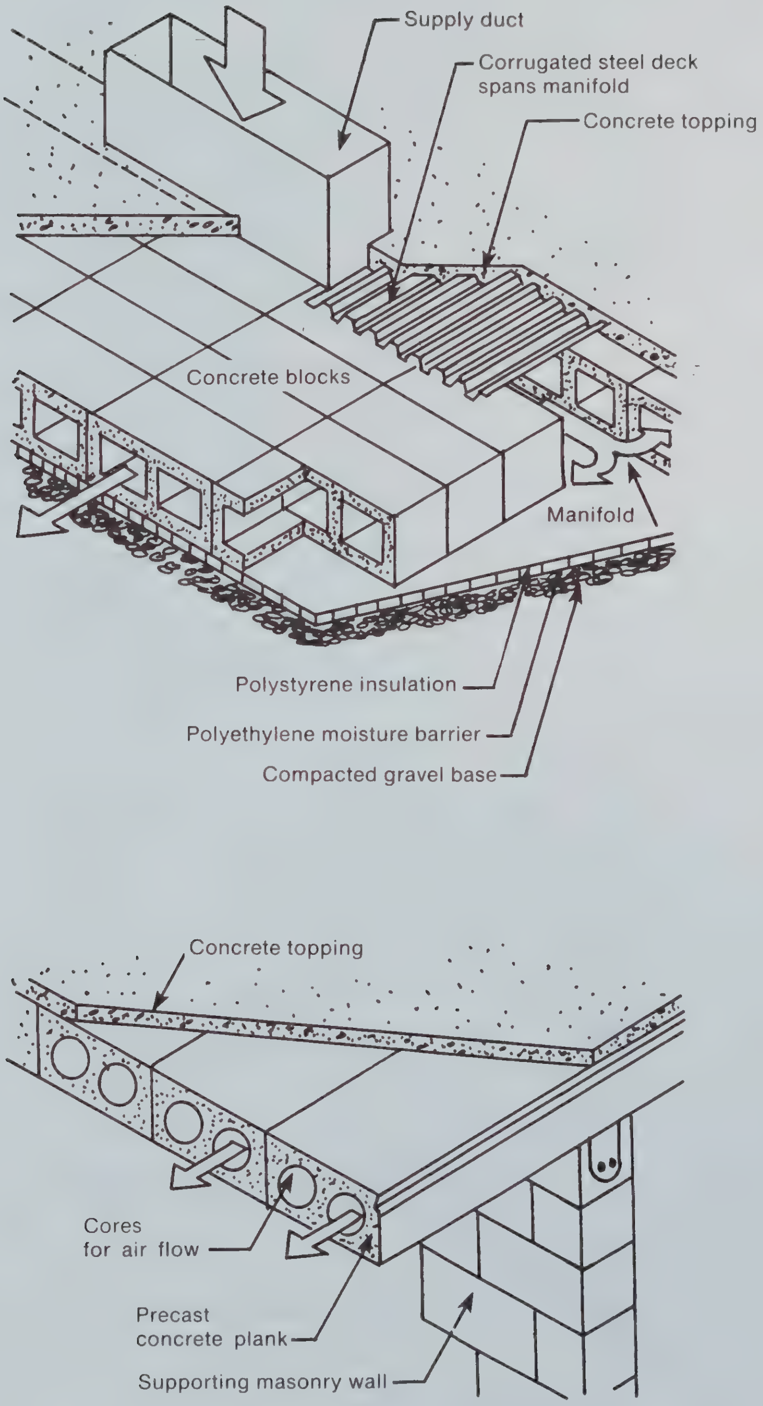


Figure 1. Five generic air-core floor systems (Lewis, 1982) (continued)

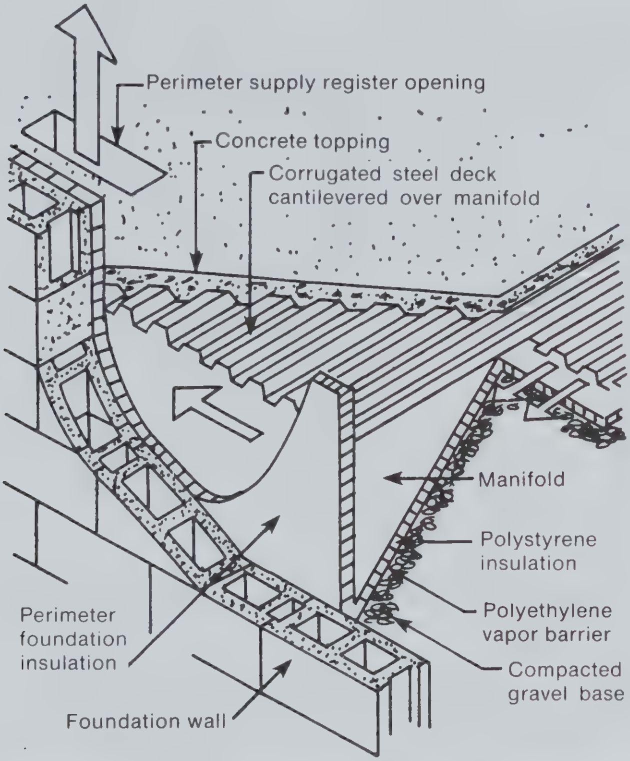

Perimeter supply register opening
Concrete topping
Corrugated steel deck cantilevered over manifold
Manifold
Polystyrene insulation
Polyethylene vapor barrier
Compacted gravel base
Perimeter foundation insulation
Foundation wall

Figure 1. Five generic air-core floor systems (Lewis, 1982) (concluded)

which Mitchell computerized for the National Concrete Masonry Association (NCMA). In a later paper he and Don Elmer (Mitchell and Elmer, 1982) describe the use of air-core walls for cooling and heating a hybrid passive home and present structural details. More structural design details are provided by Innovative Design of Raleigh, North Carolina, (Heibein, 1983) along with operational guidelines for fan sizing and control setups derived from experience on dozens of air-core structures. Stephen Heibein and I translated these basics of air-core design into simplified guidelines for the NCMA (NCMA, 1982 and 1984).

W. Scott Morris of Santa Fe, New Mexico, has taken a different approach to air-core systems (Figure 2). He designed self-balancing "block-beds" that are charged by a passive thermosiphon air-heating collector (Morris, 1983a). Measured results using embedded thermocouples indicate that the air flows freely through the block cores and heats the mass readily when driven by the good insolation of the

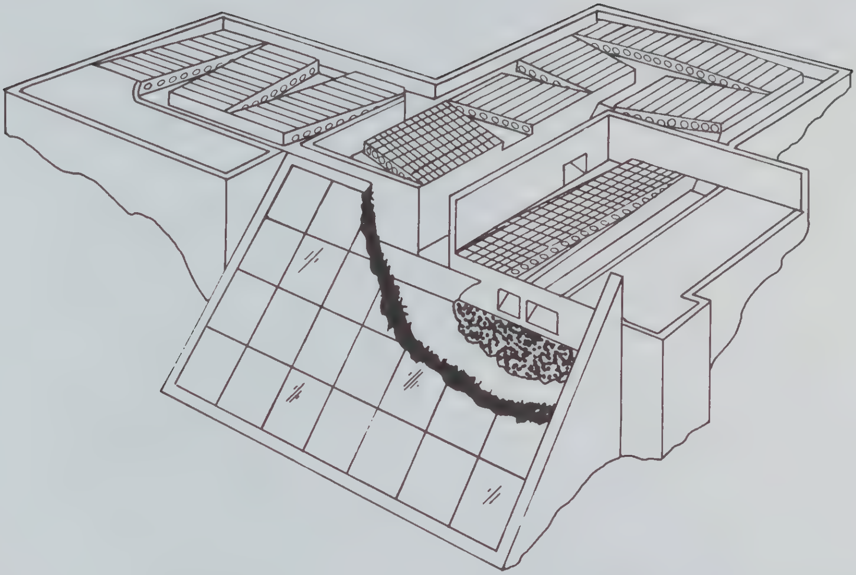


Figure 2. Air-core floor driven by a natural convection air collector (Morris, 1983a)

Santa Fe climate. The well-insulated homes were found to have high solar fractions at reasonable temperature swings (Morris, 1983b).

A Florida architect (Arenas, 1981) used a variation on air-core design in a high-mass home that vents unwanted heat gain from the envelope and uses a down-sized heat pump to reduce latent heat to complement the home's reduced sensible cooling demands. "Solara South," a typical Florida ranch style home, requires just 8000 Btu/h (2.3 kW) cooling (about 6 times less than rule of thumb) for an annual air-conditioning bill in 1981 of $162. The air-core system in this design returns air under the floor to the cooling plant.

The XENWALL system (Weil et al., 1983) uses gypsum wall board furred out on the inside of concrete block mass walls (well insulated on the exterior) designed to permit serpentine airflow (Figure 3) from the solar heat source. Typically a pre-fab sunspace attached to the building in front of a "screen block" masonry collector wall provides the heating source. The systems operate very well according to extensive monitored results obtained by XENWALL's engineers. The radiant conditioning is uniform in the XENWALL design, which enhances comfort at low energy cost. The XENWALL building system is expensive, but payback predictions based on monitored results by XENWALL indicate the cost is reasonable considering rapidly escalating prices of space conditioning.

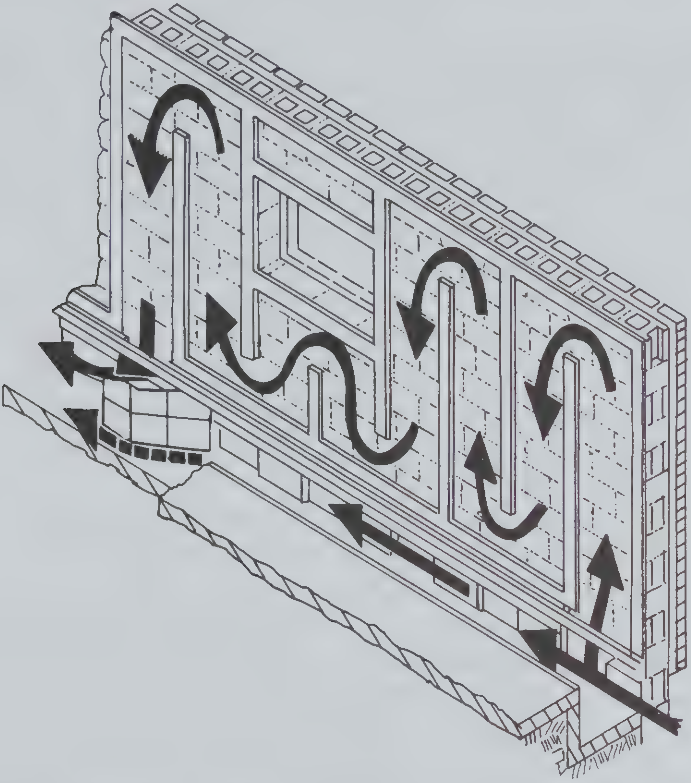


Figure 3. The XENWALL system, diagram of airflow in wall (Weil et al., 1983)

Pre-cast concrete floor decks have been designed into air-core systems for both residential and commercial buildings. One-pass, evaporatively cooled air, which is fan-forced through the cores of massive structural elements, both extracts heat and excludes the moisture-laden air from the conditioned space. Ventilation cooling through internal cores in mass can reduce the impact of latent heat otherwise added to indoor air by typical economizer ventilation cycles in humid climates. Cooling of structural mass overnight can provide a heat sink for the following day's transient cooling requirement, delaying the air-conditioning system turn-on and peak cooling demand. Interior masonry walls used by air-core cooling systems should be well sealed against air leaks. Potential for moisture migration should be analyzed in the design phase to avoid problems.

Investigators at the University of Wisconsin-Milwaukee (Johnston, 1982) designed a pre-cast, air-core, floor-plank system in a low-rise office building. The floor-plank system, which doubles as a building structure and heat distribution ducts, saves over $50,000 (1982 dollars) in first cost structural savings alone. However, these cost savings were largely offset by the $43,400 cost of the forced-air mechanical system that was required in lieu of a typical baseboard system. The analysis did not account for the cost savings of using the cores as duct work replacing normal sheet metal ducting. Electrical and plumbing costs were not changed greatly by using the floor-plank system. Net first cost savings were 3% of total building cost with the energy-efficient, floor-plank, HMHS system. The floor-plank ducts are also used for ventilation cooling. Studies showed maximum energy savings on air-core cooling occur when outdoor temperatures approach 60°F (16°C).

Experience indicates that the added costs of controlling heat flows to or from air-core structural mass are reasonable when structural materials also provide heat storage and comfort control. Maintaining structural integrity, and facilitating air-handling, comfort controls, moisture avoidance, and interior space planning are the primary concerns. HMHS systems impose few special requirements on building interior space design and layout because they are out of the way in the floor, walls, or ceilings. Their surfaces should not be covered by materials with significant R-value, but covering them with gypsum wall board, plaster, "grass cloth," wall "papers" and carpets with thin pads does not substantially reduce thermal performance.

COMPUTER SIMULATION AND DESIGN ANALYSIS

This section describes work on predicting and measuring heat transfer in the hollow core masonry "ducts." Also discussed are four NCMA studies of buildings--two residential and two small commercial--using the concrete block, air-core system from 1983 to the present.

A fundamental parameter in any design analysis is the heat transfer coefficient between the air stream and the masonry. Mitchell and Elmer (1982) use a heat transfer coefficient for concrete masonry air-core computer simulations of 0.4 Btu/h ft^2 °F (2.3 W/m^2 K). Short and Kutscher (1984) reported a derived heat transfer coefficient of about 0.28 Btu/h ft^2 °F (1.6 W/m^2 K) for a hollow core, concrete block system heated by active air collectors. In their paper they describe detailed TRNSYS simulations of an active charge/ passive discharge hybrid system, predicting that block under-floor storage would function as well or better than more common rock beds. The ASHRAE handbook (ASHRAE, 1981) lists the heat transfer coefficient of a vertical nonreflective surface as 1.47 Btu/ h ft^2 °F (8.35 W/m^2 K). A horizontal surface has a heat transfer coefficient of about 1 Btu/h ft^2 °F (5.7 W/m^2 K). Of this figure, approximately half is the convective term, which is the value relevant to air-core heat transfer because the cores can be considered to be in radiative equilibrium. Heat transfer coefficients extracted from data measured in a monitored building range from 0.23 to 0.8 Btu/h ft^2 °F (1.3 to 4.6 W/m^2 K); see the section A Monitored Building for more details.

To analyze air-core block systems, I developed an analysis approach at NCMA that uses a thermal network model of the air-core elements. The passive solar heating and thermal envelope is analyzed by the latest version of the Los Alamos SLR method published by ASHRAE (Balcomb et al., 1984). Earth temperatures are estimated by the method described by Labs and Harrington (1982). The approach can verify the potential for good building performance and helps boost confidence in the air-core systems.

Table 1 illustrates the analysis process followed by NCMA in reviewing an air-core design. The process incorporates optimizing envelope conservation and basic passive solar heating systems, evaluating the role of the interior thermal mass, and sizing the air-core system heat storage in terms of predicted auxiliary energy use and comfort needs during selected design weeks (using hourly weather data) for winter (January), summer (July), and swing season (September). With this analysis, a designer can generate needed information on the expected performance of buildings both with and without the HMHS system to use for comparison and decision making.

FOUR EXAMPLE SYSTEMS

This section discusses two homes and two commercial buildings that show both wall and floor systems. Table 2 contains general building and systems data to aid in understanding the air-core systems' role

Table 1. Air-Core Design Analysis at the National Concrete Masonry Association

---

Phase 1 Schematic Design

- LCR/NLC/Conservation
- Location of mass
- Floor or wall HMHS*
- Supply of heat
- Ventilation strategy
- Envelope, glazing, primary mass

Phase 2 Preliminary Analysis

- Detailed envelope takeoffs
- SLR results/analysis
- Optimize envelope and solar
- Configure thermal network model
- Configure weather files
- Estimate fan size for HMHS*

Phase 3 Final Analysis (Parametric Runs)

- Perimeter and underslab insulation levels
- Fan and distribution system sizing
- Hourly auxiliary predictions
  - Design heating week
  - Design cooling week
  - Swing season week
- Detection of overheating
- Correction of design if required

Prepare Report

- Envelope
- Primary passive solar
- Storage
- Auxiliary predictions
- Comfort predictions
- Discussion

*HMHS = hollow masonry heat storage system

in improving the predicted comfort and thermal performance of these four buildings.

Wildcat House

The Wildcat house, first reported at the 10th National Passive Solar Conference (Spears and Howard, 1985), is a 3100 ft^2 (288 m^2) three-

Table 2. Selected Buildings from NCMA Solar Study Data Base

Parameter[a]	Wildcat House	Syracuse House	Ithaca Funeral Home	1896 House Restaurant Addition
Location	Montgomery Co., MD	Syracuse, NY	Ithaca, NY	Western MA (Albany, NY)
Heating degree-days, °F day (°C day)	5057 (2809)	6962 (3868)	6603 (3668)	7948 (4416)
Conservation				
Wall, R (RSI)[b]	36 (6.3)	24 (4.2)	37 (6.5)	20 (3.5)
Ceiling, R (RSI)	42 (7.4)	59 (10.4)	45 (7.9)	30 (5.3)
Glass	Quad-pane	Low-e	Double	Low-e & double
Floor area, ft^2 (m^2)	3100 (288)	2200 (204)	5450 (507)	2850 (265)
Slab, R (RSI)				
perim.	15 (2.6)	12.5 (2.2)	15 (2.6)	10 (1.8)
under slab	12 (2.1)	5 (0.8)	10 (1.8)	5 (0.8)
Solar				
Type	Direct gain	Dir. gain/Sunspace	Active air	Sunspace
Glass area, ft^2 (m^2)	329 (30.6)	247 (22.6)	800 (74)	990 (92)
LCR, Btu/°F day ft^2 (kJ/°C day m^2)	20 (408)	18 (367)	23 (480)	29 (592)
NLC, Btu/°F day (kJ/°C day)	6459 (12272)	4480 (8512)	18,682 (35,496)	21,482 (40,816)
BTI, Btu/ft^2 °F (kJ/m^2 °C)[c]	1.20 (24.5)	1.98 (40.4)	2.92 (59.6)	4.93 (100.6)
Balance point, °F (°C)	57 (14)	58 (15)	62 (17)	61 (16)
SHF, %[d]	49	20	16	28
Floor/wall	Floor	Wall	Floor	Floor
Jan. pred. temp., °F (°C)				
without HMHS	58 (14)	63 (17)	57 (14)	56 (13)
with HMHS	69 (20)	71 (21)	69 (21)	70 (21)
Auxil/yr, MBtu (GJ)				
without HMHS	20.1 (21.2)	33.7 (35.5)	280.7 (295.9)	148.4 (156.4)
with HMHS	16.6 (17.5)	30.4 (32.0)	193.6 (204.1)	111.6 (117.6)

[a] $k = 10^3$, $M = 10^6$, $G = 10^9$

[b] RSI = m^2 K/W

[c] BTI = Building thermal integrity

[d] $SHF = \frac{\text{Useful solar heat}}{(\text{Total load - int. gains})}$

level, super-insulated, passive solar home. It uses 624 ft^2 (58 m^2) effective radiant area of concrete block, air-core floor topped with 3.5 in. (9 cm) of normal weight concrete in its lower level.

Design criteria called for a low-cost destratification approach and a basement floor tempering system that would recycle overheated air from the ceiling of the third level. The heat sources for the air-core floor are passive solar gains through windows, internal gains, and auxiliary heat lost from hydronic radiant floor slabs on the main and upper levels. Figure 4 shows a cross sectional schematic drawing of the Wildcat system, and Figure 5 illustrates the lower level air-core

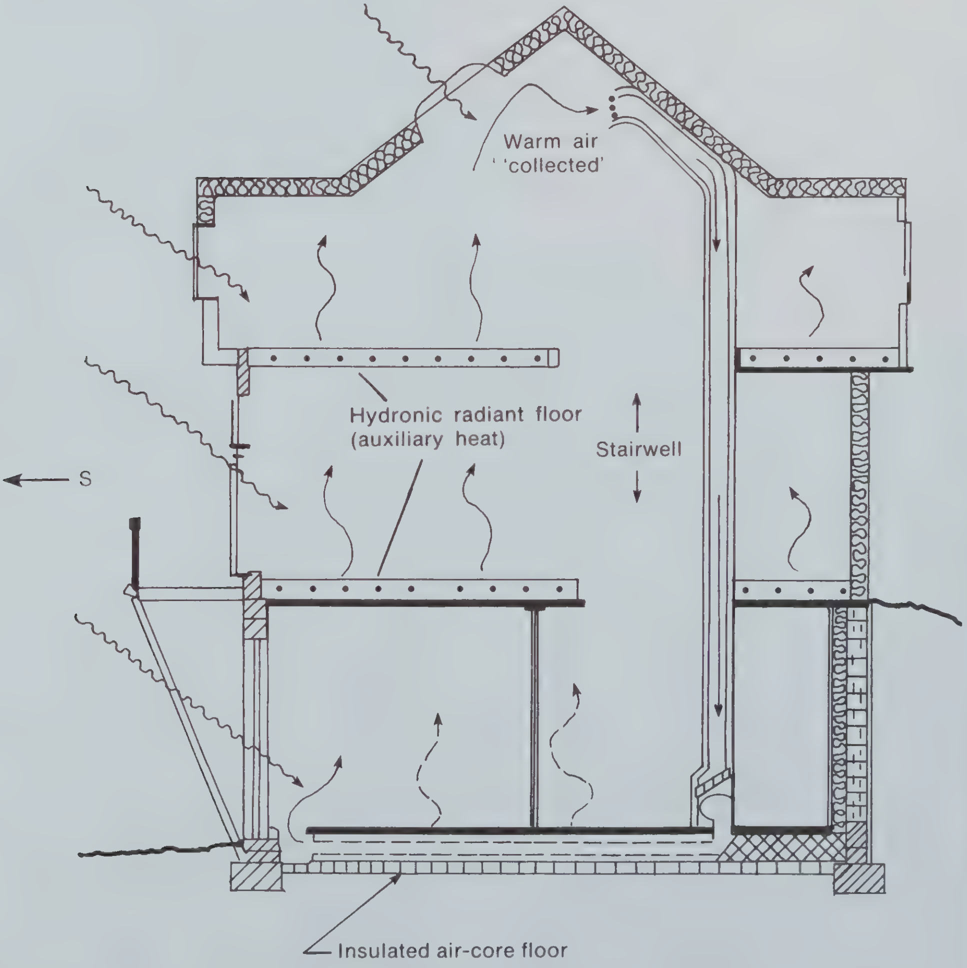


Figure 4. Wildcat house, schematic section

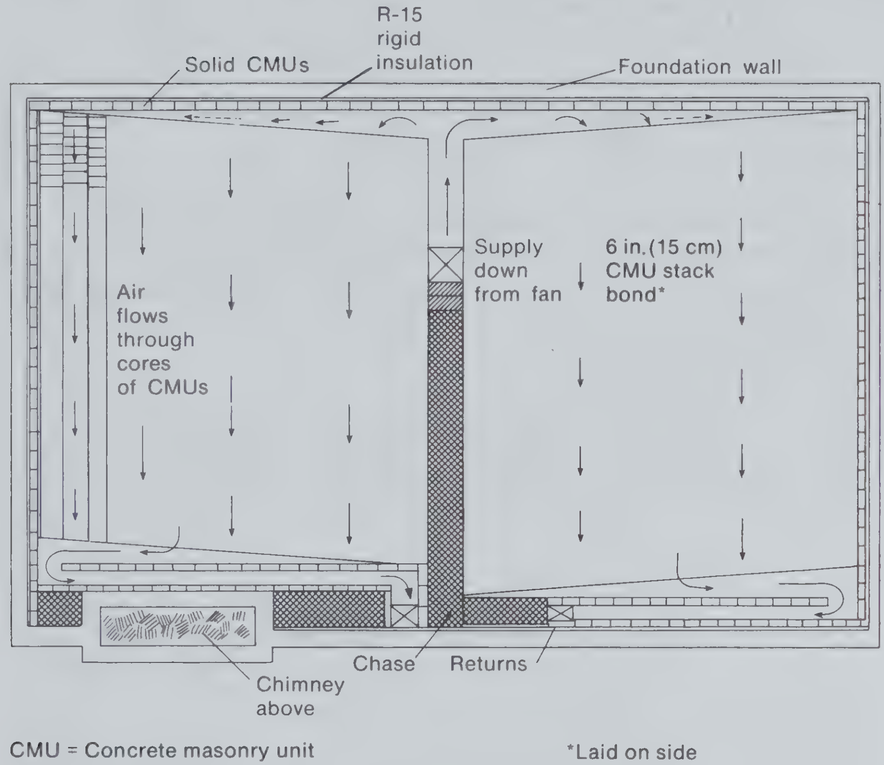


Figure 5. Wildcat house, air-core floor plan

floor layout. The supply plenum was arranged to mate with a vertical duct dropped down a stairwell. The return outlets deliver air to the base of some quad-pane glazed patio doors in the lower level. Airflow in these concrete-covered floor systems is designed to be consistent with rules of thumb on air-core run lengths (NCMA, 1984).

Analysis showed the optimal airflow rate in the block cores was 990 ft^3/min (0.47 m^3/s), which required a 1/4-1/3 hp electric motor. Pressure drop was minimal at 0.15-0.20 in. of water (2.8-3.7 mm Hg). This operating system is expected to consume about $30.00 worth of electric power per heating season at $0.07 per kWh.

Figure 6 shows winter performance of the air-core floor. The only interior mass is the hydronic radiant gyp-crete floors and a chimney in the southwest corner. A diurnal heat capacity (DHC) analysis predicted the home to have a 10°-12°F (6°-7°C) temperature swing without air-core storage. With the air-core floor the temperature swing drops to 5°F (3°C).

The floor temperature is predicted to be about 68°F (20°C) compared to 57°-59°F (14°-15°C) for typical basement slabs in this climate zone. Using air-core systems, therefore, enables basement spaces to be heated in the winter by recycling heat that otherwise would leak from the building envelope.

Flushing of the air-core system during summer nights was not effective for cooling, unlike similiar flushing of air-core interior walls

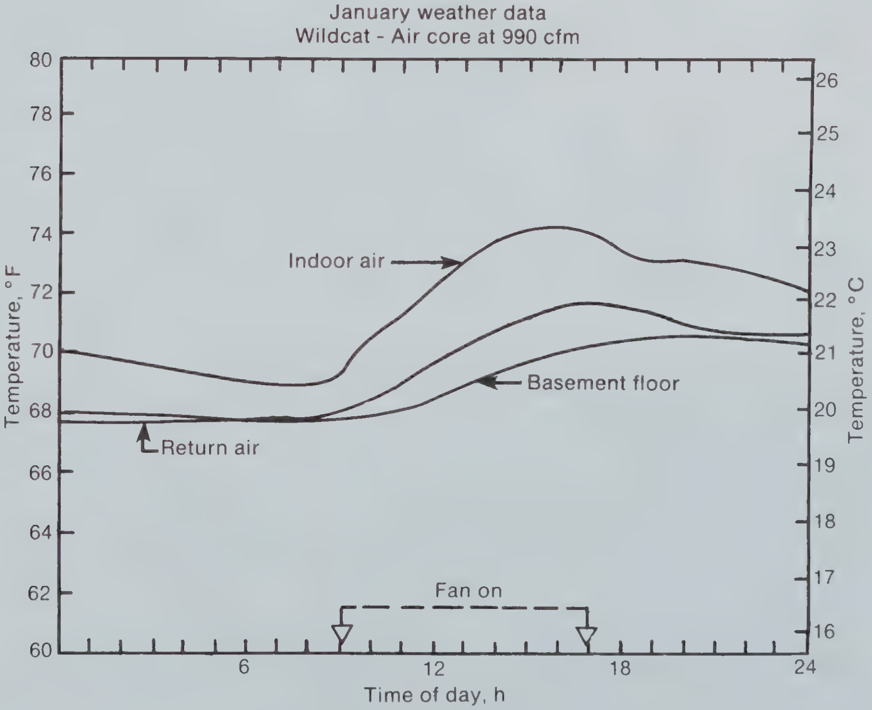


Figure 6. Wildcat house, typical air-core January performance

might be. Compared to interior walls, the surface area of the lower level floor was not very effective as a heat sink to the main living areas. The plot of typical July hourly data (Figure 7) shows the system operating in a night-flush mode. The long thermal lag of the floor is reflected in the fact that the floor temperature is about eight hours out of phase with the outdoor temperature. Because of the high levels of insulation, the indoor temperature only changes by 6°F (3°C). The floor mass cools to the earth's temperature during the day, but does not have nearly the potential for vent cooling as the outdoor night air.

The air-core system effectively extracts unwanted heat from the space and dumps it to the thermal mass from mid-afternoon to early evening, when outdoor temperatures cycled above indoor temperatures again. However, the most cost-effective strategy is to turn off the fan during the summer to avoid electric operating costs.

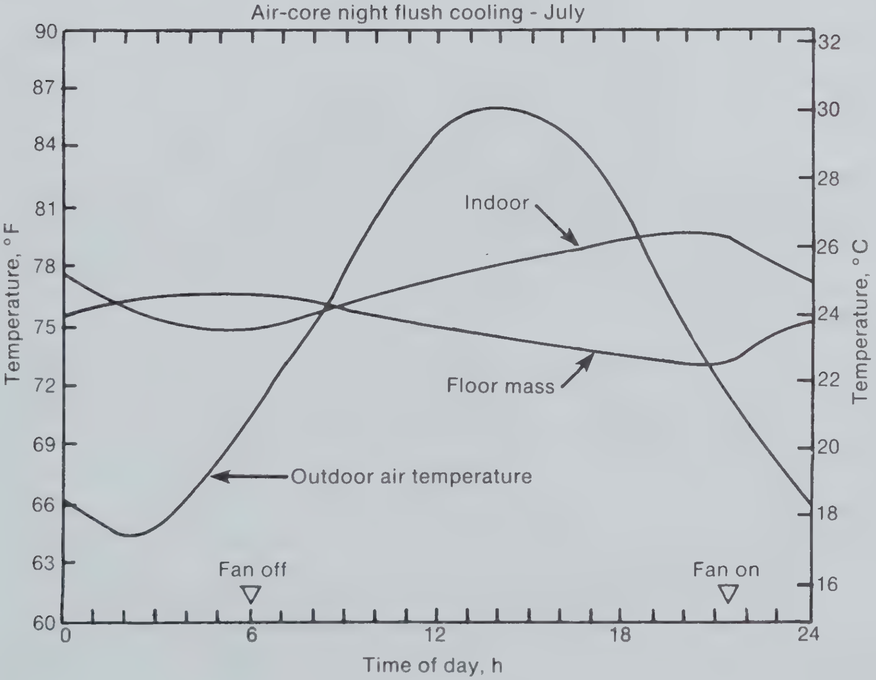


Figure 7. **Wildcat house, air-core night-flush cooling**

Syracuse House

This 2200 ft^2 (204 m^2), highly insulated, all-masonry home, built in Syracuse, New York, is patterned after a home designed for the Minnesota Masonry Institute by the Landel Corporation of Minneapolis. The original design of an air-core mass system underlying the sunspace floor was ineffective, so I altered the design to allow sunspace heat to warm the mass of an approximate 192 ft^2 (17.8 m^2) section of structural masonry wall on the north side of the home (Figure 8). Insulation lines the outside of the air-core wall, which is constructed of lightweight concrete masonry units and protected by a waterproof exterior masonry veneer. The wall is an overall R-24 (4.2 K m^2/W).

A 450 ft^3/min (0.21 m^3/s) fan draws warm air from the skylit, vertical glazed sunspace through an insulated duct and plenum arrangement to the top of the north wall and forces it down through

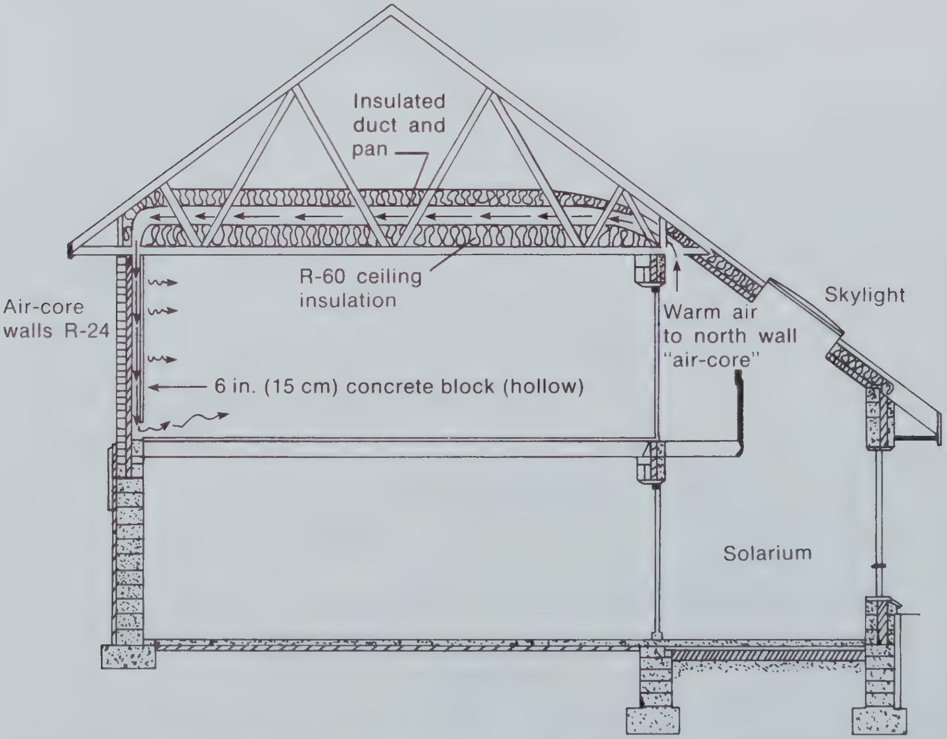


Figure 8. Syracuse house, based on an original design by Landel Corp.

the cores of the blocks. The system uses a delta-T control strategy similar to that described in NCMA (1984). The air returns from registers in the bottom row of blocks and circulates back to the sunspace via the conditioned space interior volume. A bedroom and two baths on the main level share this solar-heated north wall.

Analysis indicates that the inner surface temperature of this north wall would average 63°F (17°C) in January without the benefit of the heat storage system. With the air-core system, the wall surface temperature increases to 68°-75°F (20°-24°C), depending on the time of day and the heat output of the sunspace. The home has been occupied for nearly two years, and the owner (chairman of the NCMA Energy Committee) reports extraordinarily low energy bills for the home. Backup heating is provided by a block masonry Russian fireplace.

Ithaca Funeral Home

A super-insulated funeral home was designed and completed in mid-1983 using a low-cost 800 ft^2 (74 m^2) polycarbonate, double-glazed, site-built, vertical air collector. Hourly predictions of collector performance show outlet temperatures up to 160°F (71°C). The estimated collection efficiency of 34%-42% is above average for air collectors. The cool mass represented by this horizontal storage air-core slab boosts collector efficiency by lowering return air temperatures at the collector inlet by up to 80°-90°F (27°-32°C).

The concrete block, air-core, under-floor system provides heat storage and comfort conditioning. Cool outdoor air is circulated through the floor slab in the summer, but this operation is not recommended by NCMA. Auxiliary heating and cooling is supplied by heat pumps. The building also has an air-to-air heat exchanger because of its tight construction and occasional high occupancy. Some direct gains also contribute to heating in winter.

The floor area constructed as air-core mass storage is about 4600 ft^2 (428 m^2). The system employs a 2000 ft^3/min (0.94 m^3/s) circulator fan system, controlled by typical solar delta-T controls. The collector temperature sensor is affixed to the back of the absorber plate near the warm air outlet. Storage temperature is sensed near the outlet end of the air-core; redundant temperature probes are placed between the upper block face and the poured concrete topping. The comparison of these temperatures is used to control the fans.

The system operates like an active charge/passive discharge rock bed. However, the block under-floor system has only one-half to one-third of the calculated pressure drop of a rock bed having similar dimensions, keeping fan power requirements to a minimum. Figure 9 shows hourly predicted temperature profiles for January operation of the hybrid system. The air-core inlet temperature reflects the predicted supply temperature resulting from duct losses from the collector array to the air-core plenum. The top of the slab is about 2°-3°F (1°-2°C) warmer than room air during daytime collector operation. The mass temperature also rose about 3°F (2°C) on this January day. Room air varied between 67° and 72°F (19° and 22°C) during the 24-hour period shown, during which outdoor temperatures ranged from 15° to 28°F (-9° to -2°C). The fan turns on late because the collector array is oriented several degrees west of true south.

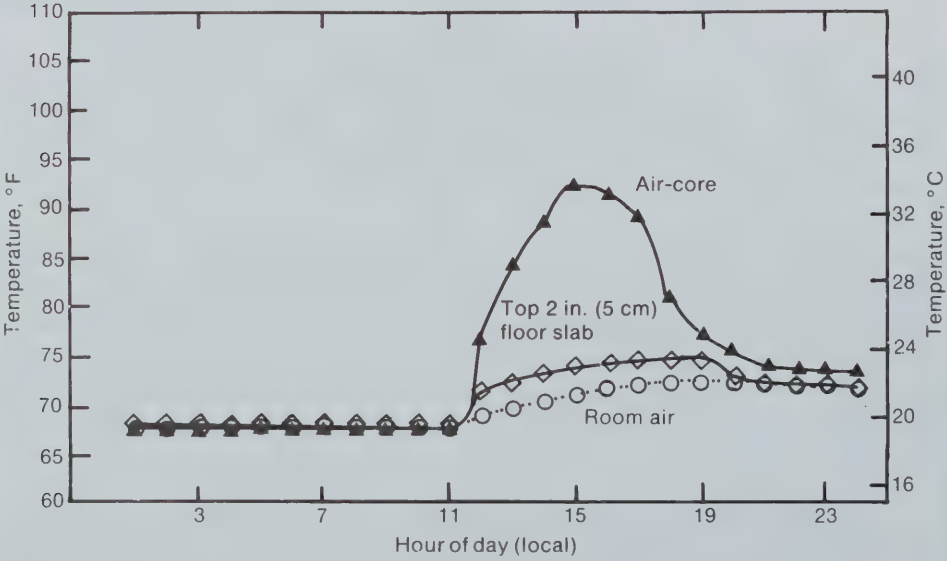


Figure 9. Ithaca funeral house, predicted temperature profile for a typical January day

Passive solar savings in this building were calculated by the SLR method as only 16%, but the $1032 (1983 dollars) energy bill for this medium-sized building is less than the bills for small homes in the region. The combined savings for conservation and hybrid solar approach $3000 based on $5.60/MBtu* natural gas. This is roughly equal to the cost of heat pump auxiliary at $0.06 per kWh, and typical heat pump coefficients of performance (COPs).

1896 House Restaurant Addition

Fred Klein, an architect of Silver Spring, Maryland, designed a large sunspace as a restaurant addition to a resort hotel. The sunspace system uses a concrete block, under-floor, heat storage system to destratify the sunspace and provide radiant heat from the floor. A total of 990 ft^2 (92 m^2) of glazing is arrayed in 524 ft^2 (49 m^2) of vertical south-facing glass and 466 ft^2 (43.3 m^2) of sloped glass tilted at 40° to horizontal.

Klein approached NCMA after preliminary analysis showed potential for overheating and elevated cooling bills for the space. Layout limitations restricted using a centralized rock bin for heat storage; moreover, Klein did not want to use forced air from a rock bin because he felt it compromised comfort. NCMA recommended a heavy block, under-floor heat storage with a 4 in. (10 cm) concrete topping. The floor was then finished in brick and quarry tile.

Analysis of the space confirmed the validity of the architect's concerns about overheating. Without the air-core system, temperature swings of 25°F (14°C) were predicted for mild, sunny September days, and wasting collected heat by venting would be necessary to control overheating on bright winter days. A 2600 ft^2 (242 m^2) effective radiant area air-core system was designed using 6-in. (15-cm) heavyweight, semi-solid, concrete masonry units. Computer thermal network analysis predicted that an airflow rate of 2000 ft^3/min (0.94 m^3/s) would be adequate, so a single fan and a well-insulated duct system were configured. With the air-core system, temperature swings were predicted to drop to a more reasonable 12°-16°F (7°-9°C). Comfort near the floor improved and thermostat settings could be lowered in winter. Floor surface temperatures in winter with the air-core were 68°-69°F (20.0°-20.6°C) with 1-in. (2.5-cm) R-5 board insulation, and 68.5°-71°F (20.3°-21.7°C) with 2-in. (5-cm) R-10 board insulation under the slab system.

---

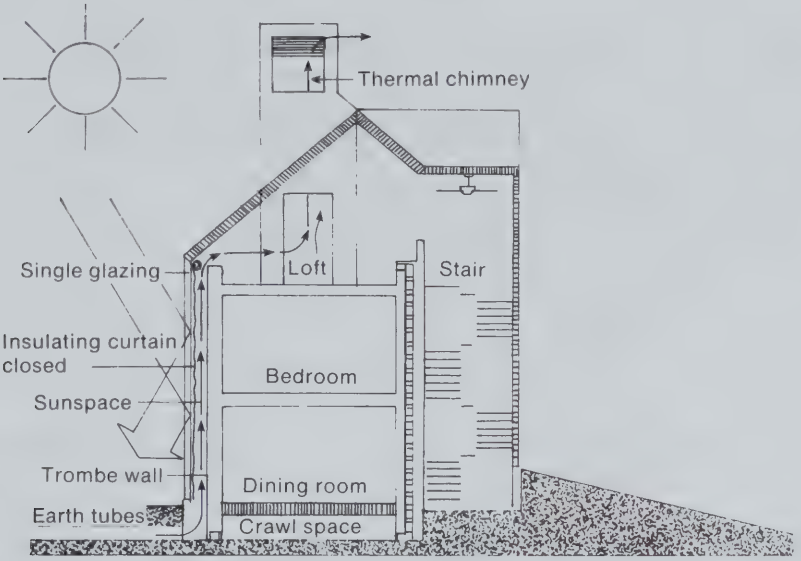
*In this article, $k = 10^3$, $M = 10^6$, $G = 10^9$

Analysis showed the most cost-effective operation in summer is to disable the fan system and let the slab temperatures float while the sunspace is vented at night. Only small cooling loads were predicted for the space, because of the mild climate, good insulation, quality wood-frame windows, and effective ventilation design. The slab did not contribute to summer cooling loads when only insulated to R-5 according to the thermal network model, which used a simplified set of nodes to earth temperature.

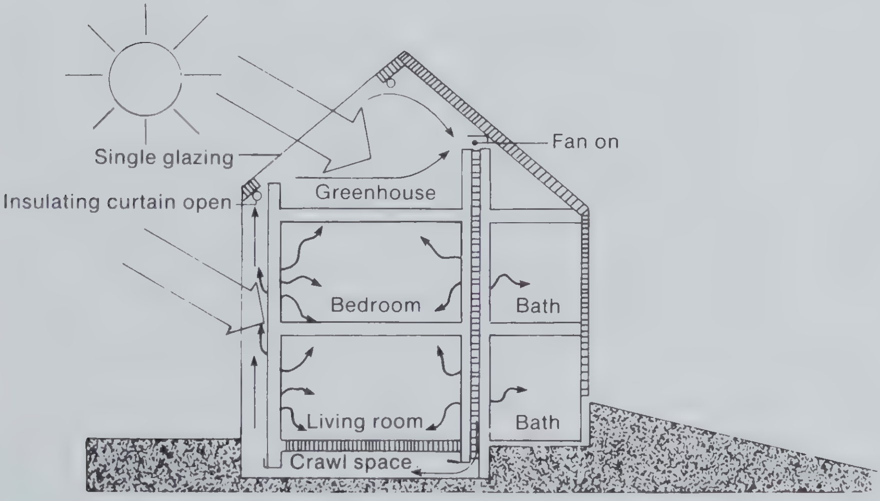
Analysis using SLR methods indicated an energy savings of $1,000/yr for the sunspace with its high mass levels. The solar heating fraction is predicted at 28%, and an estimated 112 MBtu (118 GJ) of auxiliary thermal energy is required for the sunspace. The thermal performance of this sunspace--a heat loss rate per unit of floor area per unit of indoor-outdoor temperature difference of 4.93 Btu/day ft^2 °F (1.17 W/m^2 °C)--is only slightly higher than performance figures for a well-insulated home. For a restaurant with large areas of glass to approach the performance criteria of energy-efficient residences bodes well for its economic operation.

A MONITORED BUILDING

The Roberts home (Sundance I) is a 2300 ft^2 (214 m^2), three-level, passive/hybrid solar house in Reston, Virginia, outside Washington, D.C. It has reasonable levels of insulation for its climate and a large, three-section thermal storage wall controlled by an automated thermal curtain system. It also has a sunspace on the upper level that supplies additional heat to one section of an air-core mass wall. Designed and contracted by architect W. F. Roberts, this home has won several national awards, including the built home award at the 5th National Passive Solar Conference (1980). Figure 10 shows its design in cross sections provided by the architect, and Figure 11 shows the first floor plan.



Section: summer day



Section: winter day

Figure 10. The Roberts house (Sundance I), sections

While at Vitro Laboratories, I monitored and analyzed the thermal performance of the Roberts home during portions of both the heating and cooling seasons of 1982. Results of this study were reported later by Spears (1983). I presented data on the subsystem performance of the air-core wall and the derivation of a bulk heat transfer coefficient from detailed field measured data (Howard, 1986). The detailed results of heat transfer analysis are summarized only briefly here.

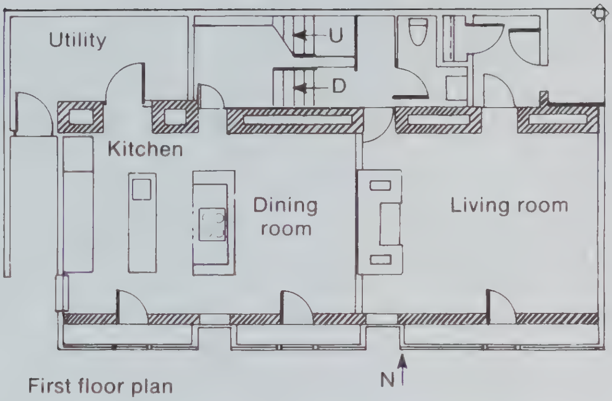


Figure 11. The Roberts house (Sundance I), first floor plan (cross hatched areas are mass walls)

General Building Performance

The Roberts home functioned well in reducing purchased auxiliary energy for space conditioning. The building had an 82% solar heating fraction and was 99% naturally cooled in 1982. Winter indoor temperatures averaged 64°F (18°C) at 25% relative humidity. Summer indoor temperatures averaged 74°F (23°C) at 51% relative humidity, despite 27% higher-than-normal cooling degree days. At \$16 per month in winter and less than \$14 per month in summer, purchased space-conditioning energy use was low as reported by Vitro (NSDN, 1980) and verified by utility bill analysis. Winter and summer energy costs include energy consumed by hybrid solar air-core fans and interior air circulation fans.

From February to May 1982 the auxiliary energy demand was 0.86 Btu/ft^2 °F day (17.5 kJ/m^2 °C day). The heating degree days are based on 65°F (18.3°C) and measured outdoor temperature. The auxiliary energy demand for February 1982 was 1.45 Btu/ft^2 °F day (30.0 kJ/m^2 °C day). The total seasonal auxiliary load coefficient calculated for a reference nonsolar home with similar conservation features was 5.13 Btu/ft^2 °F day (105 kJ/m^2 °C day).

These auxiliary energy use values are similar to auxiliary load coefficients previously reported for super-insulated buildings (Howard, 1982). The equipment load value (total building thermal load minus internal thermal gains) as supplied by auxiliary plus solar heat is about one third that thought to represent typical existing housing in the United States.

Performance for the air-core thermal storage subsystem was lumped with that of other mass storage for Vitro-NSDN seasonal reporting. However, the air-core wall's role in thermal storage was accounted for in detail in the NSDN analysis software. During February 1982, the air-core mass was recharged, accumulating 95 kBtu (100 MJ) or 30% of the total net energy accumulated in the passive primary storage mass in the building for the month. In comparison, the Trombe wall accumulated a net 147 kBtu (1,548 MJ) during the same period.

Indoor Comfort

The data show that the effective globe temperature, and hence the mean radiant temperature, in the massive, insulated enclosure, can be greater than the indoor average air temperature by as much as 4°-6°F (2°-3°C) under typical heating conditions. Strong evidence supported by heat flux plate data indicates that energy transfer by the rear air-core wall influences this phenomenon. It is observed particularly after a sunny day when the fans provide solar heated air to the air-core wall. This radiant effect is reversed in summer, when the effective globe temperature can be 5°-6°F (3°-4°C) below indoor air temperatures indicative of radiant cooling effects induced by the mass. During summer, the air-core mass is ventilated by air from earth-tubes that is impelled by pressure differences induced by twin thermal chimneys fitted at the top level of the home.

Outdoor and indoor air temperatures were monitored to assess summer comfort. According to ASHRAE comfort criteria (ASHRAE, 1981) coded into the NSDN analysis software, it was comfortable indoors for 707 of the 893 cooling hours even neglecting the beneficial effect of reduced radiant temperatures. Outdoors, only 98 comfortable hours occurred during the same period.

Air-Core Wall Heat Transfer

The heat transfer coefficients at the interior surface of the concrete masonry, air-core wall were deduced from temperature measurements. The values ranged from 0.23 to 0.80 Btu/h ft^2 °F (1.3 to 4.60 W/m^2 K). Near solar noon on the principal day studied

(February 15, 1982), the temperature difference between the solar supply air and the mass was about 30°F (17°C), and the calculated heat transfer coefficient was estimated at 0.48 Btu/h ft^2 °F (2.7 W/m^2 K). During the fan operation hours (09:00-18:00 hours), the temperature of the air-core thermal mass increased from 59° to 64°F (15° to 18°C). The calculated total energy supplied to the mass via the air-core surface area during the daily cycle was 118 kBtu (124 MJ).

Discussion

Part of the good performance of the Roberts home is attributable to the air-core mass wall, which stores excess solar heat that would have otherwise increased the envelope overheating losses from the third level. This reduction in overheating is accompanied by useful heat transfer and storage into the isolated north buffer zone that otherwise would have had to depend on natural convection for heating. The home's compact floor plan and many privacy doors reduce the distribution of heat via natural convection. Instead, the vented masonry Trombe wall and the sunspace work together with the remote air-core system to uniformly charge the entire internal thermal mass of the home. A north structural mass with no source of heat during winter could operate several degrees cooler than indoor air temperature. This effect could reduce rather than enhance indoor comfort and would boost auxiliary energy use if occupants set the thermostat higher, to offset the adverse radiant effect of a cool wall.

CONCLUSIONS

Data from monitoring results show that with high envelope thermal integrity and small south glazing areas, additional thermal mass is rarely needed beyond the heat capacity of the finish materials and furnishings typical of residential buildings (Frey et al., 1982). Designers should be mindful of issues such as overly reduced window areas, stuffy air from insufficient ventilation, and possible summer cooling and moisture problems. Glazings with improved thermal performance are now commonplace, allowing the use of larger areas without large heat loss penalties.

The use of insulated masonry walls, where heat capacity materials are exposed as interior wall surfaces, permits larger glazing areas without increasing temperature swings. As a further step, low temperature heat storage HMHS floors and walls may be charged with heated air from passive systems, interior recycled heat, or low cost, warm air active collectors. The warm heat storage surfaces can save energy by allowing good comfort levels at reduced auxiliary system thermostat settings.

Research shows heating from radiant sources located below the occupants (such as from the floor) is most comfortable. HMHS wall systems are preferred for cooling applications where floor systems could be subject to condensation if cooled to the dew point, potentially damaging carpets and other moisture-sensitive floor coverings. Cooling by means of radiant wall surfaces that are at lower temperatures than the indoor air, combined with moderate air movement, seems to create comfortable surroundings.

When analyzing the cost effectiveness of HMHS wall systems, one must account for other marginal functions of the purchased structural materials that add value to the building. A masonry heat storage wall may also support a structural load, reduce fire danger (masonry is noncombustible), reduce maintenance, and convey utilities. Such a multipurpose wall can be more cost-effective than a veneer of exotic, high cost heat storage material purchased *only* to serve as heat storage. HMHS wall systems need not interfere with the normal layout of spaces and may be covered by ordinary trim materials having low R-values without much sacrifice in performance.

In slab-on-grade passive solar homes with larger glazing areas, an under-floor HMHS system is desirable in terms of both energy and comfort. An HMHS system can be especially useful in reducing indoor overheating in the fall in climates with moderate ambient afternoon temperatures combined with high insolation at low solar angles. Slabs for such a passive building are generally already well insulated and include a vapor retarder, which reduces the marginal cost of protecting the HMHS system from losses to the earth. The cost of the slab's concrete is unchanged, so the marginal cost of the air-core system is for the block, the plenum deck-forms, the insulated ducting from the source, the controls and sensors, and the circulating fan with mounting hardware.

Parametric studies may be used to minimize airflow rate for effective charging of the air-core slab mass. Differential controls are used with conservative operating points to minimize the time the fan is on to periods of useful temperature difference from heat source to heat sink. This results in minimized parasitic electric power and better net savings, lower fan noise, and better comfort. I have shown in unpublished analysis that well-sized, differential controlled, HMHS systems can deliver COPs from 2.5 to 10 depending on building thermal integrity and the nature of the heat source.

In summary, the air-core system offers designers another low-cost option for including heat and cool storage in the initial design stage rather than adding it on later at less competitive cost. Objections to space and aesthetic impositions can be reduced by making heat storage systems part of the structure rather than simply attachments. Low cost structural materials like concrete block, precast floor planks, metal forms, and brick cavity walls are most commonly used.

The main reasons why HMHS systems are generating considerable excitement are summarized as follows:

- Low additional cost because of new arrangements of familiar construction materials
- Simplicity of design, control, and maintenance
- Low-cost operation because of minimum system pressure drops and small fan-power demands
- Passive or active solar heat sources, wood stove heat, or recycled heat can be used
- Design can be flexible for minimum interference with architectural program
- Efficient use of solar heat at lowest possible temperatures
- Thermal recycle function can reduce envelope losses from overheating or venting
- Destratification and moderation of temperature swings of solar driven spaces enhances comfort level
- Radiant heat and cool delivery avoids drafts and discomfort associated with more common fan systems

- Air-to-air heat exchanger systems can be easily incorporated to boost indoor air quality.

Although the HMHS system has been computer simulated by NCMA in the design phase of several residential and light commercial buildings, more work is necessary to develop simplified design methods for air-core systems based on a detailed analytical data base. The concrete masonry industry will rapidly transfer this information to eager users when it becomes available.

ACKNOWLEDGMENTS

This article, written while I was with the National Concrete Masonry Association, discusses results of work performed for U.S. DOE - National Solar Data Network and NCMA. The opinions expressed in this paper are mine, however, and do not reflect the policy of U.S. DOE, NCMA, or NAHB.

REFERENCES

ASHRAE, 1981. *ASHRAE Handbook: 1981 Fundamentals*. Chapter 8. New York: ASHRAE.

Arenas, F., 1981. Solara South: passive/hybrid cooling for Florida's hot humid climate. *Passive Cooling: Proc. Int. Passive and Hybrid Cooling Conf.* (Miami Beach, FL, Nov. 6-16, 1981) Boulder, CO: ASES, pp. 110-112.

Balcomb, J.D., R.W. Jones, R.D. McFarland, and W.O. Wray, 1984. *Passive Solar Heating Analysis*. Atlanta, GA: ASHRAE.

Frey, D.J., J.N. Swisher, and M.J. Holtz, 1982. Class B performance monitoring of passive and hybrid solar buildings. *Proc. ASME 1982 Solar Division Conf.* pp. 571-577.

Heibein, S., 1983. The aircore system. *Concrete Masonry Solar Architecture Quarterly*. Herndon, VA: National Concrete Masonry Association.

Howard, B.D., 1982. Comparing NSDN passive solar buildings with selected superinsulated houses. *Proc. 7th National Passive Solar Conf.* (Knoxville, TN, Aug. 30-Sept. 1, 1982) Boulder, CO: ASES.

Howard, B.D., 1986. Aircore systems for passive and hybrid energy conserving buildings. *ASHRAE Transactions* 92(2).

Johnston, S.A., 1982. Passive solar and hybrid manufactured building systems: precast concrete applications - The Spancrete project. *The Renewable Challenge: Proc. 1982 Annual Meeting.* (Houston, TX) Boulder, CO: ASES, pp. 855-860.

Labs, K., and K. Harrington, 1982. Comparison of ground and above ground climates for identifying appropriate cooling strategies. *Passive Solar Journal* 1(1):4-11.

Lewis, S., 1982. Radiant floors. *Solar Age* (May):42-44.

Mitchell, R., and D. Elmer, 1982. A unique use of concrete block for cooling applications. *The Renewable Challenge: Proc. 1982 Annual Meeting.* (Houston, TX) Boulder, CO: ASES, pp. 649-654.

Mitchell, R., and J.E. Giansante, 1979. The use of concrete block directly under a concrete slab as a heat storage system in a passive solar heated building. *Alternative Energy Sources II.* pp. 399-411.

Morris, W.S., 1983a. Radiant heating: from balloons to blockbeds. *Solar Age* (August):16-20.

Morris, W.S., 1983b. Performance evaluation of a thermosyphon/blockbed system. *Proc. 8th National Passive Solar Conf.* (Santa Fe, NM, Sept. 7-9, 1983) Boulder, CO: ASES, pp. 265-269.

NCMA, 1982. *TEK-120: Second generation passive solar systems with concrete masonry.* Herndon, VA: National Concrete Masonry Association.

NCMA, 1984. *TEK-140: Air-core design guidelines.* Herndon, VA: National Concrete Masonry Association.

National Solar Data Network, 1980. SOLAR/0003-80/17. (Available from TIC, Box 63, Oak Ridge, TN 38554.)

Short, W., and C.F. Kutscher, 1984. *Analysis of an active charge/passive discharge solar space conditioning system employing air collectors and hollow core concrete block floor.* SERI/SP-253-2340. Golden, CO: SERI.

Spears, J.W., 1983. *Solar Energy System Performance Evaluation - Roberts Home.* SH/SC SOLAR/1122-83/14. Silver Spring, MD: Vitro Laboratories.

Spears, J.W., and B.D. Howard, 1985. Conservation, solar, mass and auxiliary - a balanced approach. *Proc. 10th National Passive Solar Conf.* (Raleigh, NC, Oct. 15-20, 1985,) Boulder, CO: ASES, pp. 209-214.

Weil, S. et al., 1983. Uniform radiant conditioning. Region X ASHRAE Conf. (Reno, NV) (Available XENARX Corp., 1063 15th Street, Sparks, NE 89431.)

Passive Solar Journal, 3(3), 277-290 (1986)

Natural Convection in a Passive Solar Building

Allan T. Kirkpatrick, Dallas D. Hill, and Kirk W. Stokes
Department of Mechanical Engineering
Colorado State University
Fort Collins, Colorado 80523

Abstract

Experiments are described that were conducted at the full-scale Reconfigurable Passive Test (REPEAT) facility at Colorado State University. We measured velocity and temperature profiles in the doorways between a sunspace and adjoining north rooms. The results are presented in terms of a series of velocity and temperature profiles for different times of day.

INTRODUCTION

The performance of comfortable, energy-efficient, passive solar-heated buildings depends on natural convection flow processes.

Copyright © 1986 by Marcel Dekker, Inc.

Natural convection is a means by which thermal energy is transferred from one part of the building to another without the use of mechanical devices. The natural convection path or loop in a building usually involves flow from a heated room through a doorway to a remote room, then back to the heated room through either the same doorway or a different one. In a recent issue of *Passive Solar Journal*, Anderson (1986) reviewed natural convection research as it relates to passive solar building applications.

The driving mechanism of natural convection heat transfer is the temperature difference across the doorways between the north and south zones of a building. The temperature difference implies that the air on one side of the doorway is of a different density than the air on the other side. From the principle of hydrostatics, where pressure is proportional to density times depth, the pressure difference across the doorway varies with height. This pressure difference causes air to accelerate and convect through the doorway.

Passive solar-heated buildings, since they are strongly coupled to the radiative and convective thermal environment through the south facing glazing, can have large internal temperature differentials. The south portion of a building can be either warmer or cooler than the north portion of a building, which will create natural convection inside the building.

In this paper we examine the natural convection flow profiles through partitions or doorways in a multizone passive solar building. The objective is to show the dependence of the magnitude and direction of the natural convection on the interior stratification and surface temperatures. We present measurements of the temperature and velocity profiles in the doorways, related measurements of the thermal stratification in the zones, and the interior wall temperatures. As shown in Figure 1 we chose a common three-zone passive solar geometry: a two-story sunspace connected to upper and lower north rooms by single doorways.

Workers at Los Alamos National Laboratory have measured doorway flow profiles in passive solar buildings over the last five years, specifically Weber and Kearney (1980), Balcomb et al. (1981, 1983, and 1985), and White et al. (1985). They measured these profiles near noon on sunny days in occupied buildings. While natural convection through doorways was not always taken into account in the architectural design of the building, such convection was found to account for a major fraction of heat transfer from one part of the building to another. Researchers involved in these studies recommended that sunspaces connected to the rest of the building by doorways be considered an essential component of passive solar design. They found that passive return air ducts were unnecessary because of their small cross-sectional area relative to doorway area.

Analytical modeling of doorway flow has relied on Bernoulli's equation, which relates the velocity of the air in the doorway to the temperature difference across the doorway via a doorway discharge coefficient. Brown and Solvason (1962) performed early work in this area. Balcomb and his coworkers generally use the Bernoulli's equation approach to correlate the observed heat transfer through doorway openings with the temperature difference across the openings.

Since the thermal environment of a passive solar building is not constant, one would expect that the flow profiles in the doorways between zones are also not constant. The largest flow rates, of course, would be expected at solar noon at maximum solar power because of the relatively low thermal capacitance of the air. However, prior to our work, no measurements of the flow profiles at other times of the day had been done. Such measurements would help assess the daily performance of the passive solar heating components. In addition, measurements of the flow profile through the doorway in the horizontal direction have not been previously reported.

DESCRIPTION OF EXPERIMENT

The experiments were performed in the full-scale Reconfigurable Passive Test (REPEAT) facility at Colorado State University. This research facility is designed to study the thermal performance of two-story, large residential, or small commercial passive solar buildings. The facility is 10 m (33 ft) on a side, and 7 m (23 ft) high. For these experiments the building was configured into three zones: a two-story sunspace and an upper and lower north room as shown in Figure 1. The sunspace and north rooms are connected by

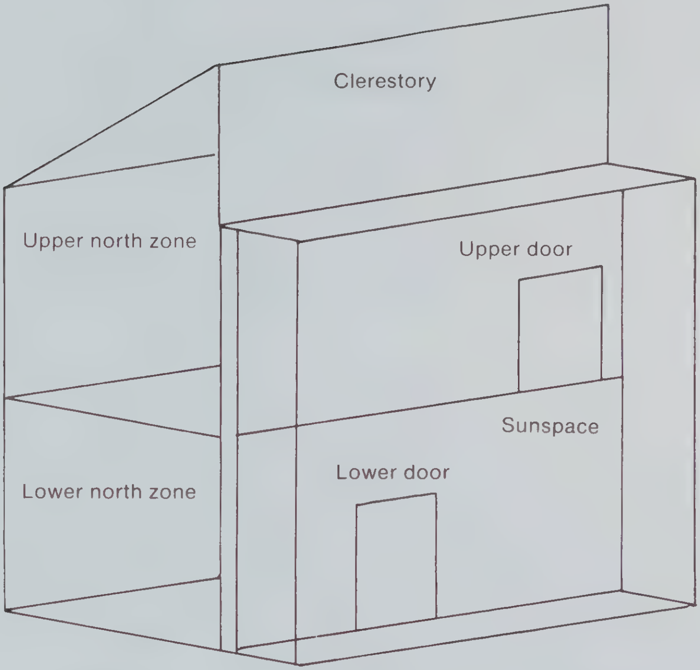


Figure 1. **Building schematic of the REPEAT facility, Colorado State University**

single doorways in a 20 cm (8 in.) thick brick storage wall. The doorways are 2.02 m (6.6 ft) high and 0.71 m (2.3 ft) wide, so the total doorway area is 2.87 m^2 (30.9 ft^2). The doorways were always open during the tests. The sunspace has 80 m^2 (860 ft^2) of south-facing glass. The upper north zone has 17 m^2 (180 ft^2) of south-facing clerestory glazing, with the rest of the interior surfaces being conventional gypsum wall. The upper and lower north zones are connected by a horizontal opening of the same area as a doorway, which was designed to model a stairway. The thermal capacitances of the upper and lower north zones differ greatly because the lower north walls and floor are composed of 25 cm (10 in.) thick concrete and the upper zone is of lightweight wood frame construction.

We measured the air temperatures in each zone by arrays of shielded thermocouples. The shields are concentric aluminum cylinders approximately 10 cm (4 in.) long and 5 cm (2 in.) in diameter. Thermocouples embedded in the surfaces measure the interior surface temperatures of gypsum, concrete, and glass. We used a Datametrics hot wire anemometer, which was calibrated periodically in a low speed wind tunnel, to measure the doorway velocity profiles.

Doorway temperature profiles were measured with a thermocouple. An adjustable ringstand support held the hot wires and thermocouples in place. We took data every 20 cm (50 in.) on the vertical centerline of each doorway. The uncertainty in the velocity measurements is 0.02 m/s (0.07 ft/s). The absolute uncertainty in the temperature measurements is 0.1°C (0.2°F). The data acquisition sequence began at the bottom of the upstairs doorway grid and finished at the top of the downstairs doorway grid. We did not take data in the horizontal opening. Each acquisition period lasted approximately 10 minutes. An HP3497A microvoltmeter connected to an HP86 computer collected the data.

RESULTS

We measured the velocity and temperature profiles in the doorways and zone air and surface temperatures over the course of a month in the late spring. During this time, the sun did not shine directly into the sunspace because of the overhangs. The glass, brick wall, and floor of the sunspace were heated by the diffuse solar radiation. Measurements were taken at hourly intervals.

The diagrams in Figure 2 show the general behavior of the three-zone geometry. Each diagram represents the thermal state of the building at a particular time. The solid line is a cross section of the building, the dashed lines in the doorways represent the temperature and velocity profiles, and the dotted lines in the center of each zone represent the temperature profile in the zone. Three temperature scales are shown for the north zone, doorway, and sunspace, respectively. The velocity scale is plotted along the top of the building. Also shown are the interior surface temperatures.

At 5:30 a.m. just before sunrise, as shown in Figure 2a, the flow through each doorway is unidirectional, forming a natural convection loop in the building. The flow profile in the upper doorway is similar to a slug profile, and the flow profile in the lower doorway is like a horizontal wall jet. The thermal stratification in each doorway is small. The unidirectional motion of the air can be explained in terms of the temperature difference between the north and south walls. Note that the diagrams in Figure 2 are labeled with eight surface temperatures. The temperature of the surface of the north

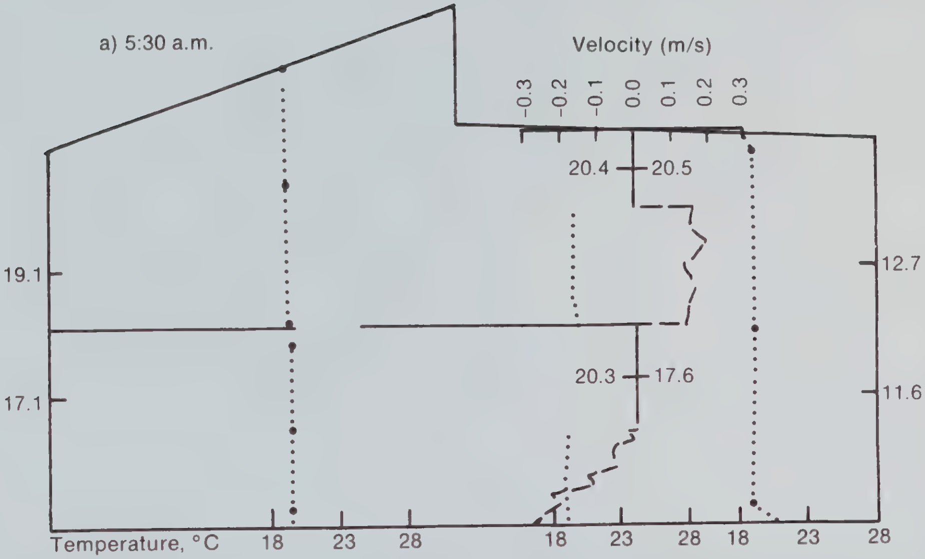


Figure 2a. Temperature and velocity profiles in the REPEAT facility. Surface temperatures are in °C. Dashed lines are velocity profiles. Dotted lines are temperature profiles.

wall, both at the first and second story, is about 18°C (64°F); and the temperature of the inside of the glazing of the two-story sunspace is about 12°C (54°F). So, the entire south side of the building can be considered relatively cold, and the entire north side can be considered relatively hot. This is the classical enclosure with differential heating from the side, which produces unidirectional flow as seen in the doorways. The region of zero velocity, defined as the neutral plane, is located somewhere between the two doorways.

At about an hour after sunrise at 6:30, the flow velocities are near zero, and by 8:30 a.m., the flow has reversed. As shown in Figure 2b, the flow through each doorway is unidirectional, but in the opposite direction. The flow loop is now counter-clockwise. Both flow profiles are similar to horizontal wall jets. The largest velocities in the upper door are at the top. The flow is being driven by the temperature difference of about 6°C (11°F) between the upper sunspace glazing and the lower north zone wall. The stratification in the sunspace is about 2°C (4°F), while in the taller north zones, it is about 3°C (5°F). The stratification is generally linear, and in the two north zones, it is offset. Note that the floor of the lower north zone and the sunspace is cooler than the air above it, and the ceiling of the upper north zone and the sunspace is cooler than the air below it.

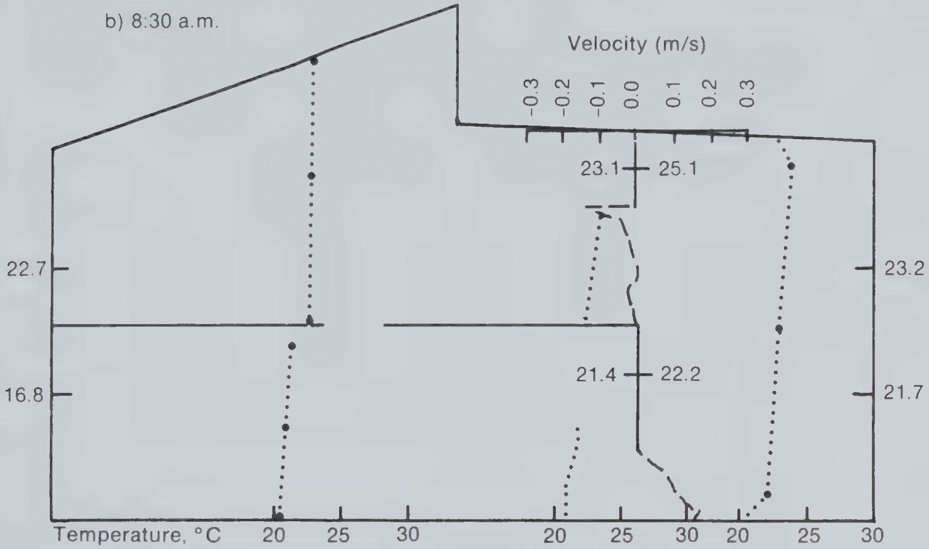
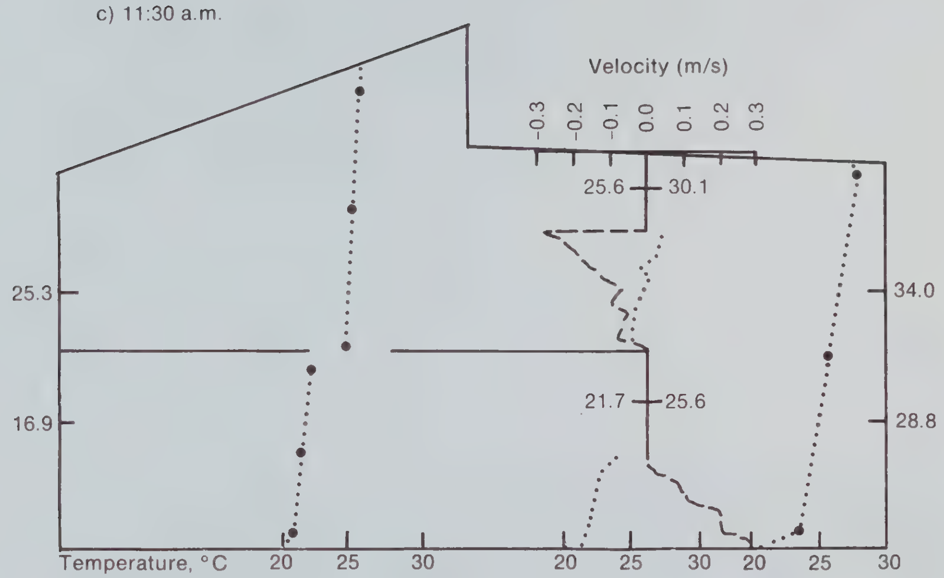


Figure 2b. Temperature and velocity profiles in the REPEAT facility. Surface temperatures are in °C. Dashed lines are velocity profiles. Dotted lines are temperature profiles. (Continued)

During the morning the magnitudes of the flow velocities and the thermal stratification in the doorways increase. The thermal state of the building at 11:30 a.m. is shown in Figure 2c. The entire south glazing is now warmer than the entire north wall, which accounts for the strong counter-clockwise flow. The net heat transfer from the sunspace is about 800 W (2700 Btu/h). The temperature difference between the upper glazing and the lower north wall is 17°C (31°F). The thermal stratification in the sunspace is primarily linear, at about 4°C (7°F), while it is 5°C (9°F) in the north zones.

Maximum solar power is reached around noon. The thermal state of the building at 1:30 p.m. is shown in Figure 2d. The overall flow pattern is still generally in the counter-clockwise direction. The flow in the upper door is still unidirectional, with the velocity increasing at the bottom of the door. The flow in the lower door is now slightly bidirectional. The net heat transfer from the sunspace is about 600 W (2000 Btu/h). Because of the clerestory and the small thermal capacitance of the upper north zone wall, the temperature of the upper north zone wall has risen significantly higher than the lower north zone wall. The flow is now being driven by the temperature difference between the entire south glazing and the lower north wall. The stratification in the sunspace and the north zones is about



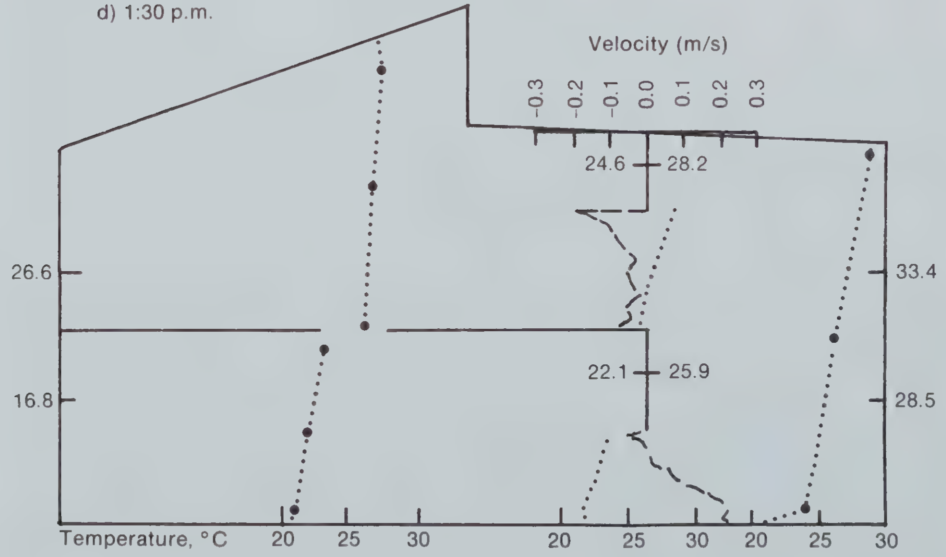


Figure 2c&d. Temperature and velocity profiles in the REPEAT facility. Surface temperatures are in °C. Dashed lines are velocity profiles. Dotted lines are temperature profiles. (Continued)

5° and 6°C (9° and 11°F), respectively. A neutral plane is now located in the bottom doorway.

The temperature and flow profile at 4:30 p.m. are shown in Figure 2e. The flow through both doorways has decreased, but is still unidirectional. The bottom doorway has a jet-like profile, and the upper doorway has a curious u-shaped profile. The south glazing temperature is cooler relative to earlier readings. The stratification in the sunspace is now 4°C (7°F), and has remained constant at about 6°C (11°F) in the north zones.

Finally, the thermal state at 7:30 p.m. is shown in Figure 2f. Bidirectional profiles now exist in both doorways, clockwise for the upper door and counterclockwise for the lower door. Note that the highest and lowest interior surface temperatures are on the same wall, namely the north wall, with the south glazing and storage wall temperature somewhere in between. The flow loops in the upper and lower north zones appear to be separate from one another. The stratification in the sunspaces and the north zones is about 3°C (5°F). There are now two neutral planes, one in each doorway.

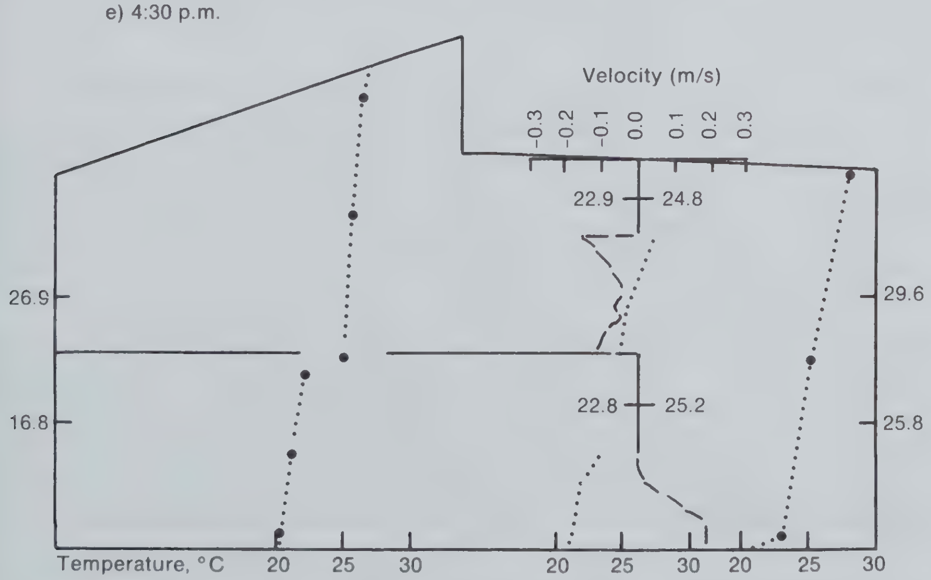


Figure 2e. Temperature and velocity profiles in the REPEAT facility. Surface temperatures are in °C. Dashed lines are velocity profiles. Dotted lines are temperature profiles. (Continued)

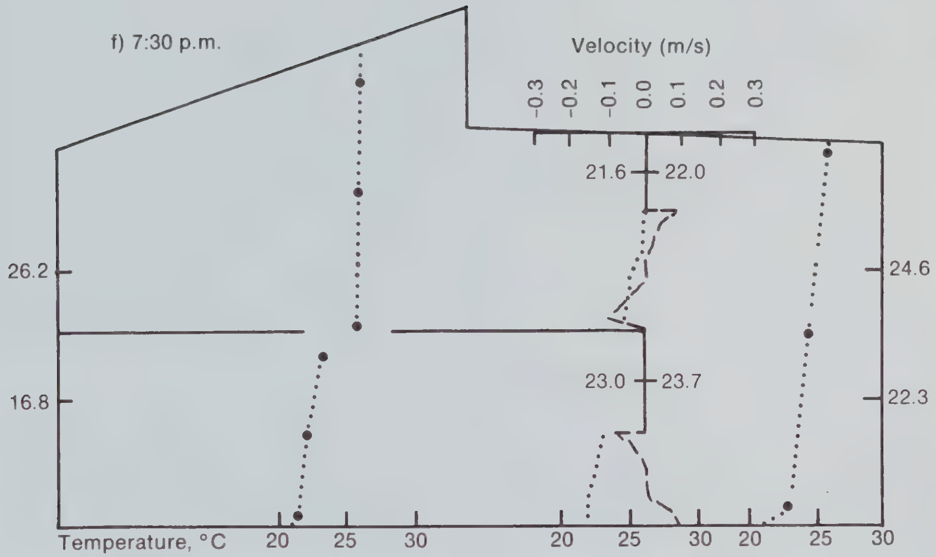
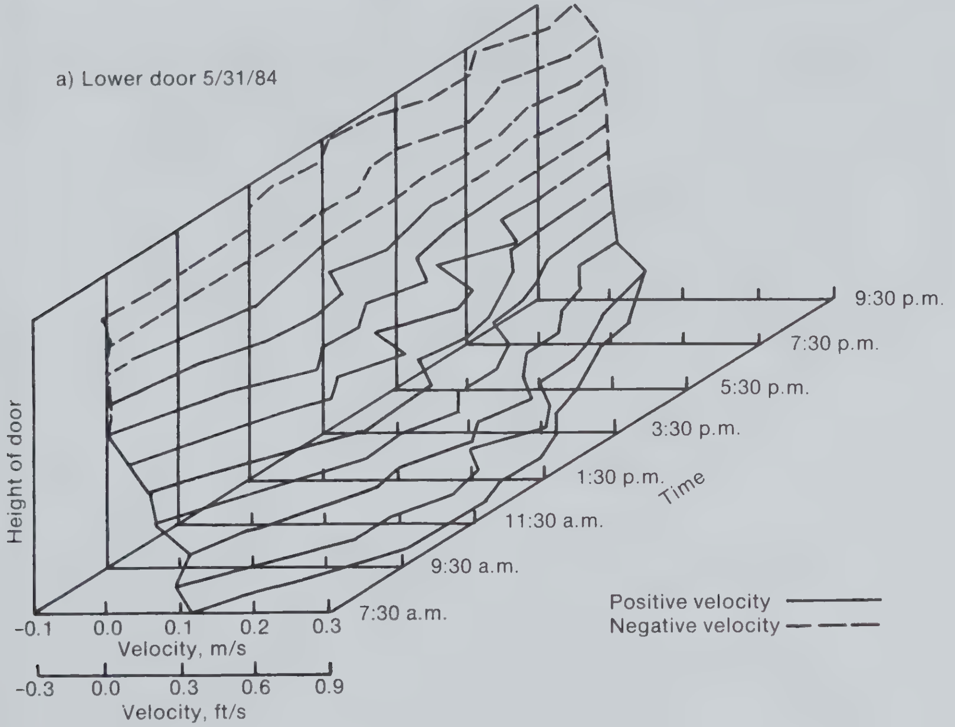


Figure 2f. Temperature and velocity profiles in the REPEAT facility. Surface temperatures are in °C. Dashed lines are velocity profiles. Dotted lines are temperature profiles. (Concluded)

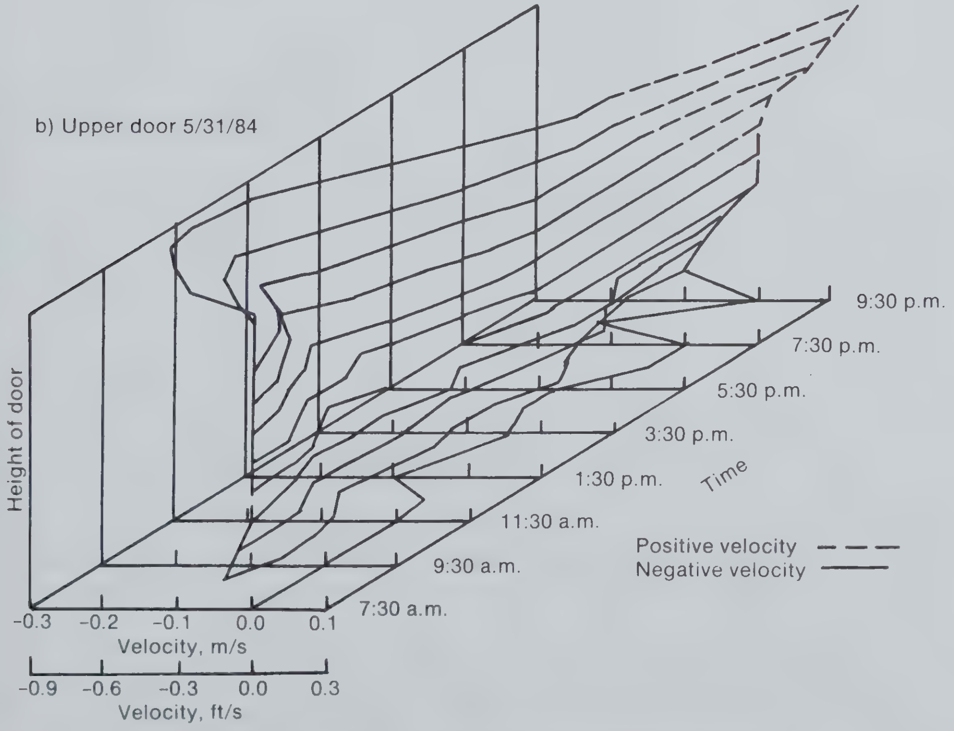
The thermal stratification in the doorways for the six times shown is usually slightly steeper than the stratification in the upstream zone because of the compression of the streamlines through the doorway.

Figures 3a and b show three dimensional plots of the velocity profiles versus time. The figures illustrate the changing nature of the flow profiles through the doorways during the day. The maximum flow velocities through the doorways range from 0.1 to 0.3 m/s (0.3 to 1.0 ft/s). The largest flow rates are near noon because of the relatively low thermal capacitance of the air.

Figure 4 shows the variation of the velocity through a doorway in a horizontal plane. These velocities were measured at five different heights in the lower doorway. The velocity profile in a horizontal plane is not constant, but varies by about 10%. The maximum velocity is not necessarily at the centerline; in fact, the centerline velocity is slightly smaller than the velocity on either side of it. This is probably due to the combined effect of the natural convection boundary layers and zonal flow. The average velocity obtained by integrating the velocities across a horizontal location is also shown. Note that the average velocity is either slightly greater or less than the centerline velocity.



a) Lower door 5/31/84



b) Upper door 5/31/84

Figure 3. Velocity profile versus time for the lower doorway

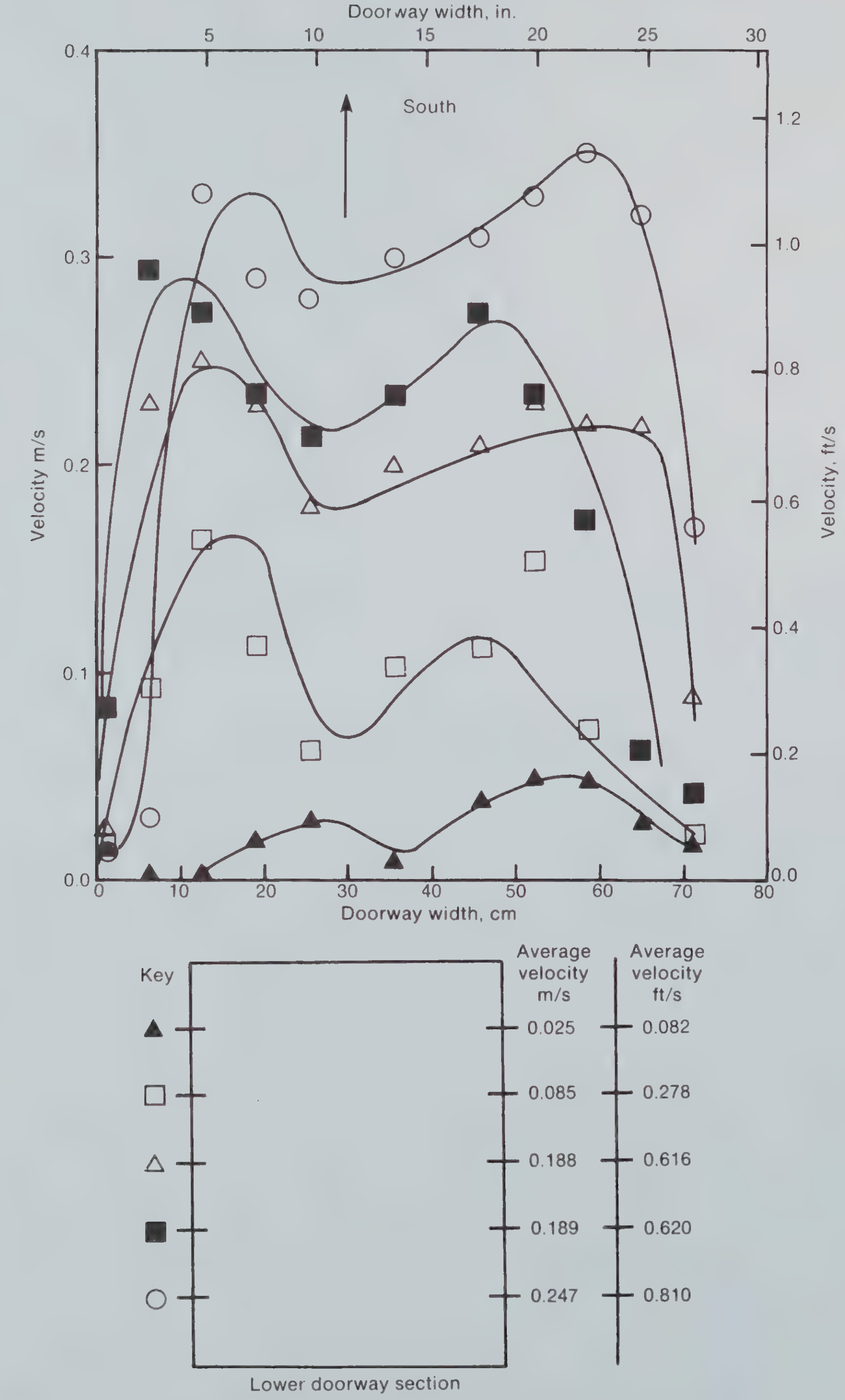


Figure 4. Horizontal velocity profiles in the lower doorway

The doorway velocity and temperature profiles can be integrated to give the net convective heat transfer from the sunspace to the rest of the building. This information is contained in Hill, Kirkpatrick, and Burns (1986), in which the Bernoulli equation approach was extended to include multiple openings and stratified zones. They correlated the net heat transfer with the temperature difference across the doorways. Fisher, Bohn, and Anderson (1985) have compared these REPEAT doorway velocity profiles with scale model simulation and correlated the doorway velocity profiles with the north and south interior wall temperatures.

CONCLUSIONS

The natural convection flow profiles through the doorways of a full scale building are complex and change in time. The flow profiles through the doorway can be both unidirectional and bidirectional. The magnitude and direction of the flow can be interpreted in terms of the relative temperatures of the north and south walls of the building.

ACKNOWLEDGMENTS

We are grateful to C. Byron Winn at Colorado State University and J. Douglas Balcomb at Los Alamos National Laboratory and Solar Energy Research Institute for their support and encouragement. This work was supported by the Gas Research Institute.

REFERENCES

Anderson, R. 1986. Natural convection research and solar building applications. *Passive Solar Journal* 3(1):33-76.

Balcomb, J.D. 1981. Heating remote rooms in passive solar buildings. *Solar World Forum: Proc. International Solar Energy Society Congress.* (Brighton, England, Aug. 23-28, 1981) Oxford: Pergamon Press, pp. 1835-1839.

Balcomb, J.D., and G.F. Jones, 1985. Natural convection airflow and heat transport in buildings: experimental results. *Proc. 10th National Passive Solar Conf.* (Raleigh, NC, Oct. 15-20, 1985) Boulder, CO: ASES, pp. 88-92.

Balcomb, J.D., and K. Yamaguchi, 1983. Heat distribution by natural convection. *Proc. 8th National Passive Solar Conf.* (Santa Fe, NM, Sept. 7-9, 1983) Boulder, CO: ASES, pp. 289-294.

Brown, W.G, and K.R. Solvason, 1962. Natural convection through rectangular openings in partitions. *Int. J. Heat Mass Transfer* 5:859-868.

Fisher, E., M. Bohn, and R. Anderson, 1985. Model simulation of building air flow: comparison with the CSU REPEAT facility. *Proc. 10th National Passive Solar Conf.* (Raleigh, NC, Oct. 15-20, 1985) Boulder, CO: ASES, pp. 99-104.

Hill, D., A. Kirkpatrick, and P. Burns, 1986. Analysis and measurements of interzonal natural convection heat transfer in buildings. *J. Solar Energy Engineering* 108(3):178-184.

Weber, D.D., and R.J. Kearney, 1980. Natural convection heat transfer through an aperture in passive solar heated buildings. *Proc. 5th National Passive Solar Conf.* (Amherst, MA, Oct. 19-26, 1980) Newark, DE: AS/ISES, pp. 1037-1041.

White, M.D., C.B. Winn, G.F. Jones, and J.D. Balcomb, 1985. The influence of geometry on natural convection in buildings. *Proc. 10th National Passive Solar Conf.* (Raleigh, NC, Oct. 15-20, 1985) Boulder, CO: ASES, pp. 75-81.

Passive Solar Journal, 3(3), 291-320 (1986)

Passive Solar Buildings in Italy

Gabriella Funaro
ENEA (National Committee for
Nuclear and Alternative Energies)
Casaccia (Rome), Italy

Abstract

Until recently, few data have been available on passive solar buildings in Italy. A survey conducted by the National Committee for Nuclear and Alternative Energies (ENEA) identified 130 buildings and collected information on them. Solar features used in these buildings include sunspaces and greenhouses, Trombe walls, direct gain, and thermosiphoning air panel systems. Traditional architectural elements such as balconies are also being used as energy-saving features. This article discusses seven of the buildings that were selected for their interesting designs and good thermal performance.

Copyright © 1986 by Marcel Dekker, Inc.

INTRODUCTION

Bioclimatic architecture, which emphasizes low-energy design, was introduced into Italy in 1978 by energy-conscious architects and designers. Government demonstration programs initiated after 1981 encouraged this new architectural approach and its use of passive solar technologies. Although many passive solar buildings were constructed both independently and as a result of the demonstration programs, few data have existed on them until recently. Consequently, Italian solar buildings have been represented internationally by only a limited sample of these bioclimatic buildings.

Today, however, a survey conducted by the National Committee for Nuclear and Alternative Energies (ENEA) has brought to light much information about Italy's passive solar buildings. The survey identified 130 buildings and gathered information from questionnaires filled out by operators responsible for the projects. Table 1 shows the regional distribution of these buildings. The discrepancy between numbers of buildings per region--some regions boast many buildings while other regions have none--has several possible explanations. Some regions such as Piedmont and Tuscany have demonstration programs that fund the construction of experimental buildings. In other regions, local authorities encourage construction, as in the case of the numerous passive solar schools near Rome that were built by the Province. Finally, some regions have public or private enterprises that constructed passive solar buildings for their own use.

Residential buildings account for 74% of the buildings in the survey (Figure 1). Of the total number of homes, only 10% are detached. This percentage is low because, until recently, public money for demonstration projects went only to low-income housing, which tends to be multifamily buildings. The multifamily buildings, which account for 64% of the buildings, amount to a total volume of 447,000 m^3 (15.8 million ft^3), or more than 1800 apartments.

The buildings identified in the survey incorporate a broad spectrum of passive solar technologies. Sunspaces or greenhouses are found in 65 buildings, Trombe walls in 14, and thermosiphoning air panel

Table 1. Regional Distribution of Passive Solar Buildings

Region	No. Projects	%	No. Bldgs.	%	No. Apts.	%	Volume 10^3 m^3	Volume 10^3 ft^3	%
Piemonte	21	24.1	25	21.7	533	30.0	141	4990	21.2
Trentino A.A.	1	1.1	1	0.9	---	---	9	300	1.3
Veneto	9	10.3	18	15.6	121	6.8	51	1790	7.6
Friuli V.G.	10	11.5	17	14.8	452	25.5	105	3700	15.7
Liguria	4	4.6	6	5.2	143	8.1	41	1450	6.2
E. Romagna	9	10.3	12	10.4	154	8.7	100	3520	15.0
Toscana	11	12.6	12	10.4	293	16.5	75	2640	11.2
Marche	5	5.7	5	4.3	22	1.2	25	880	3.7
Abruzzo	1	1.1	1	0.9	1	---	0.3	10	---
Lazio	9	10.3	11	9.5	1	---	97	3410	14.5
Puglia	1	1.1	1	0.9	16	0.9	2	80	0.3
Basilicata	1	1.1	1	0.9	9	0.5	3	110	0.5
Calabria	2	2.3	2	1.7	6	0.3	3	120	0.5
Sicilia	3	3.4	3	2.6	24	1.4	15	540	2.3
Total	87	99.5	115	99.8	1775	99.9	667	23540	100.0

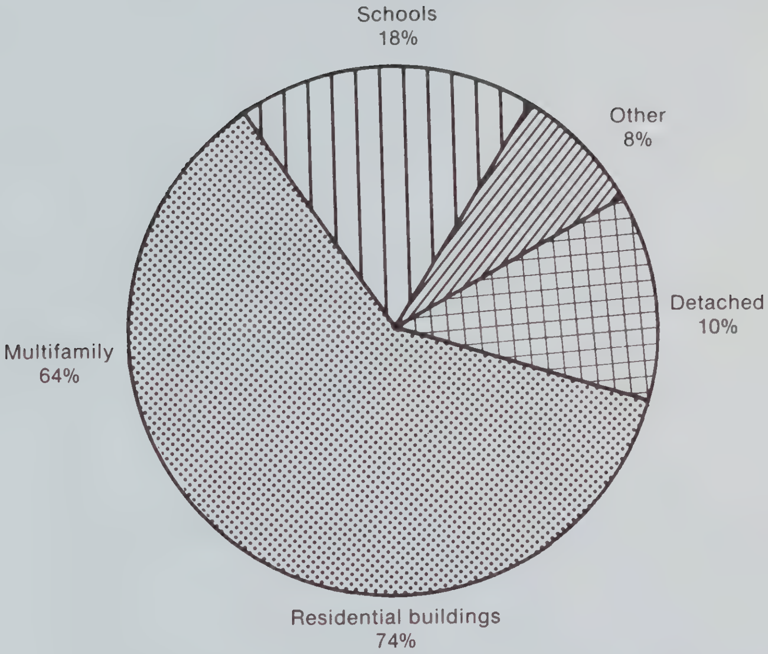


Figure 1. Building types

(TAP) systems in 14. Most of the buildings have big, double-glazed windows that serve as direct gain systems. Many architectural elements characteristic of Italian construction, such as heavy mass materials and components, shading devices, and different kinds of thermal shutters, are now being used in an energy-conscious way. Other elements, such as balconies and loggias, are being redefined and transformed into passive components. In addition, 82% of the passive solar buildings have water or air collectors for active solar heating and domestic hot water needs.

Few of the passive solar projects are retrofits to existing buildings. Little attention is paid in Italy to the energy problems of existing buildings. This fact either reflects the attitude of some authorities who consider passive solar systems to be suitable only for new construction, or is a result of certain legal barriers to the modification of existing buildings. For example, enclosing a balcony to form a sunspace might violate the building code if the sunspace is regarded as a heated volume and the space-heating equipment is not sized upward accordingly. Interestingly, whereas in other countries this type of retrofit would be considered progressive and desirable, in Italy it is regarded as "abusive construction."

Fifty-four buildings will be monitored to gather experimental data and performance results. Some performance predictions are available, such as the amount of energy needed to keep the internal temperature at the design value for a year. But not all designers used the same method to compute the performance, so the results are not always reliable and comparable (Figure 2).

Using anticipated performance results, architects and designers can produce reliable design tools for the next, more mature generation of passive solar buildings. Through 1984 the projects have grown both in number and size (Table 2 and Figures 3 and 4), but continued growth is questionable. A new generation of passive buildings, we hope much larger, will evolve only when design and construction lessons are assimilated from the first generation.

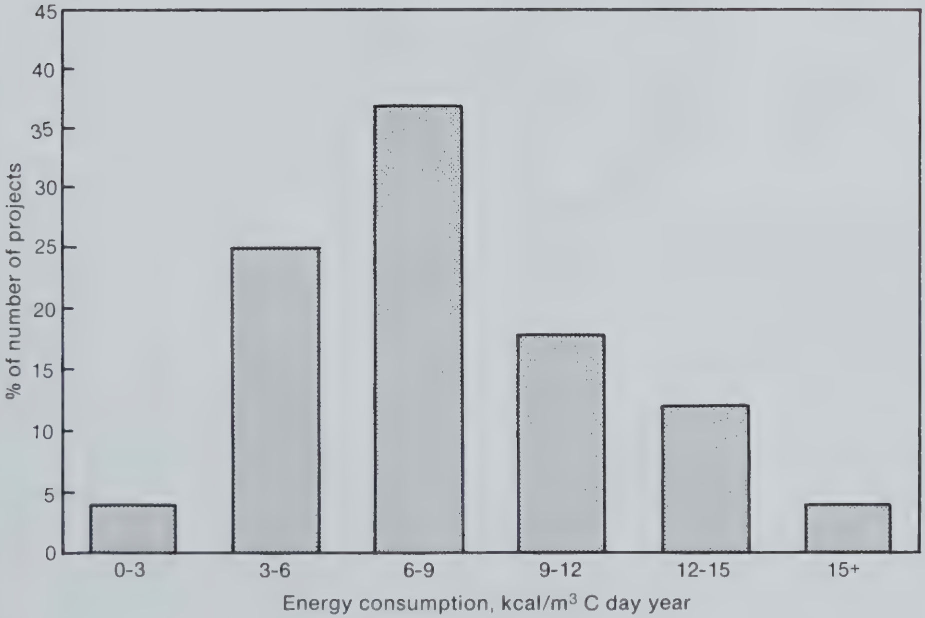


Figure 2. Energy consumption predictions per unit of building volume per degree-day. (Note: 1 kcal = 4182 J; 1 kJ/m^3 °C day = 14.9 Btu/ft^3 °F day)

Table 2. Project Summary by Year

Year	No. Projects	%	No. Bldgs.	%	Volume 10^3 m^3	10^3 ft^3	%
Before 1980	6	7.4	6	5.5	9	310	1.3
1981	5	6.2	5	4.6	18	630	2.8
1982	11	13.6	20	18.3	76	2670	11.6
1983	13	16.0	14	12.8	62	2200	9.6
1984	28	34.6	38	34.9	274	9692	42.1
After 1985	18	22.2	26	23.9	213	7520	32.6
Total	81	100.0	109	100.0	652	23022	100.0

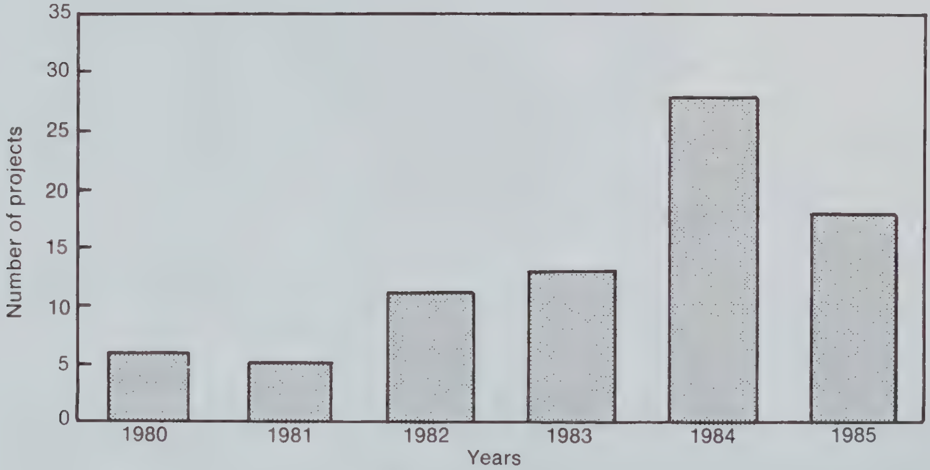


Figure 3. Number of projects per year

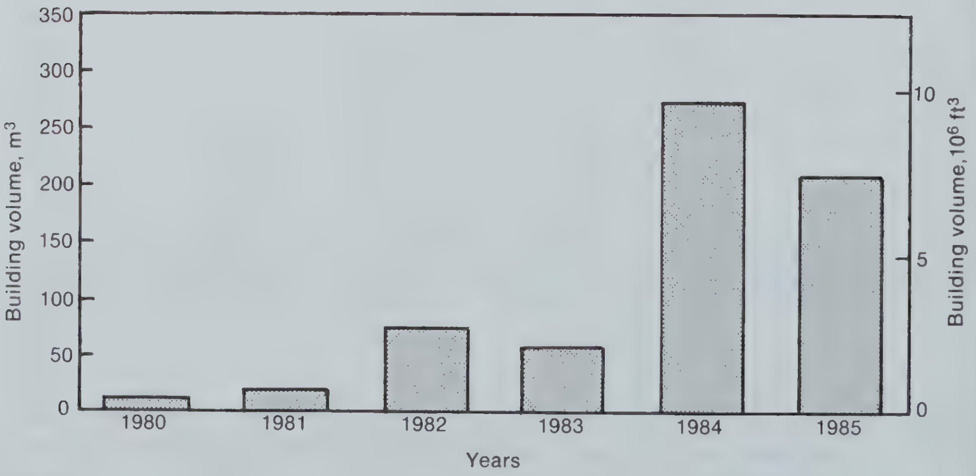


Figure 4. Building volume per year

The rest of this article discusses seven of the most interesting Italian passive solar buildings. Located in northern, central, and southern Italy, these buildings were selected from the total sample because of their interesting architectural designs and good thermal performances. The complete sample is reported in Funaro, Fanchiotti, and D'Errico (1985).

ORBASSANO APARTMENT BUILDING

Location: Orbassano (Turin)
Latitude: 45°N
Degree-days: 2570°C-day (4630°F-day)
Date of Completion: 1982
Heated Volume: 9800 m^3 (346,000 ft^3)
Number of Apartments: 40
Number of Floors: 10

This building is one of 16 experimental buildings whose construction was sponsored by the European Community and the Italian Housing Committee. These buildings were constructed from 1982 to 1984 throughout the Piedmont region in northern Italy.

This particular building is trapezoidal (Figures 5, 6, and 7) with 190 m^2 (2040 ft^2) of vertical air collectors integrated on the south face. These panels are used for space heating and hot water (Figure 8). There are 560 m^2 (6030 ft^2) of double-glazed, continuous sunspaces on each southeast and southwest wall. The total heated volume is 1800 m^3 (63,600 ft^3). The north side, insulated with 4 cm (1.6 in.) of polystyrene on the external face of the wall, has very few openings, and all the windows, reinforced with steel frames, have double glass to reduce heat loss. The sunspaces are expected to meet 36% of the total thermal load. Estimated thermal performance results are shown in Table 3.

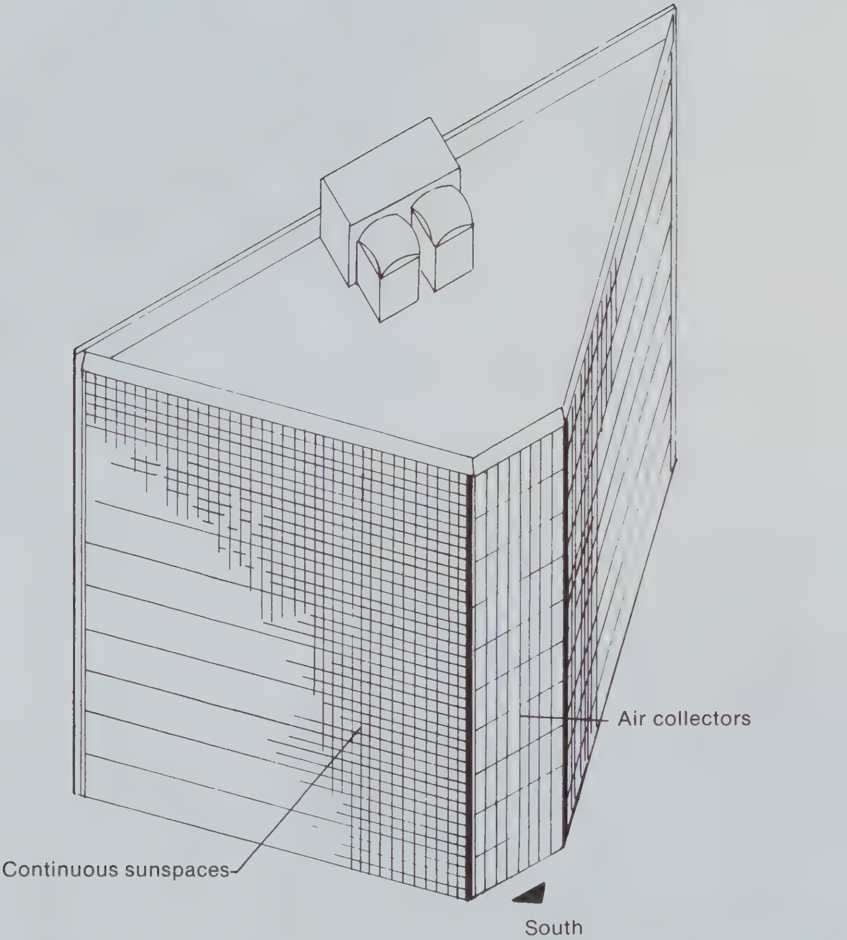


Figure 5. Orbassano apartment building, axonometric

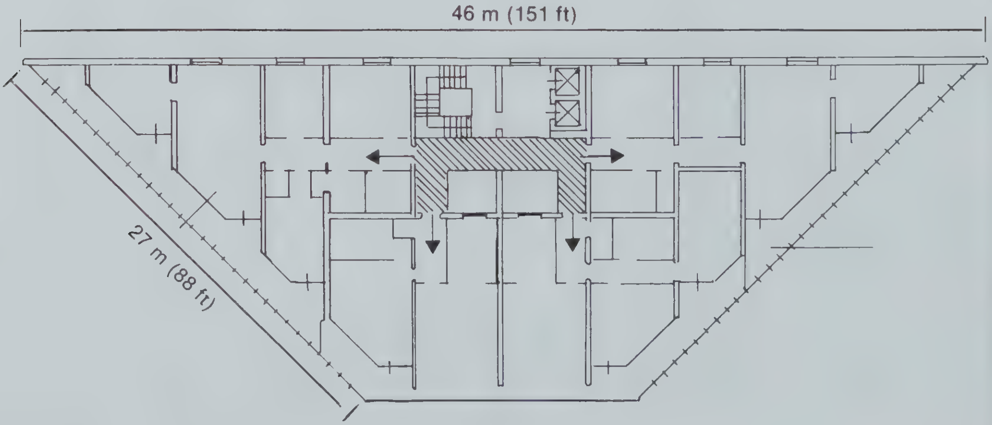


Figure 6. Orbassano apartment building, plan

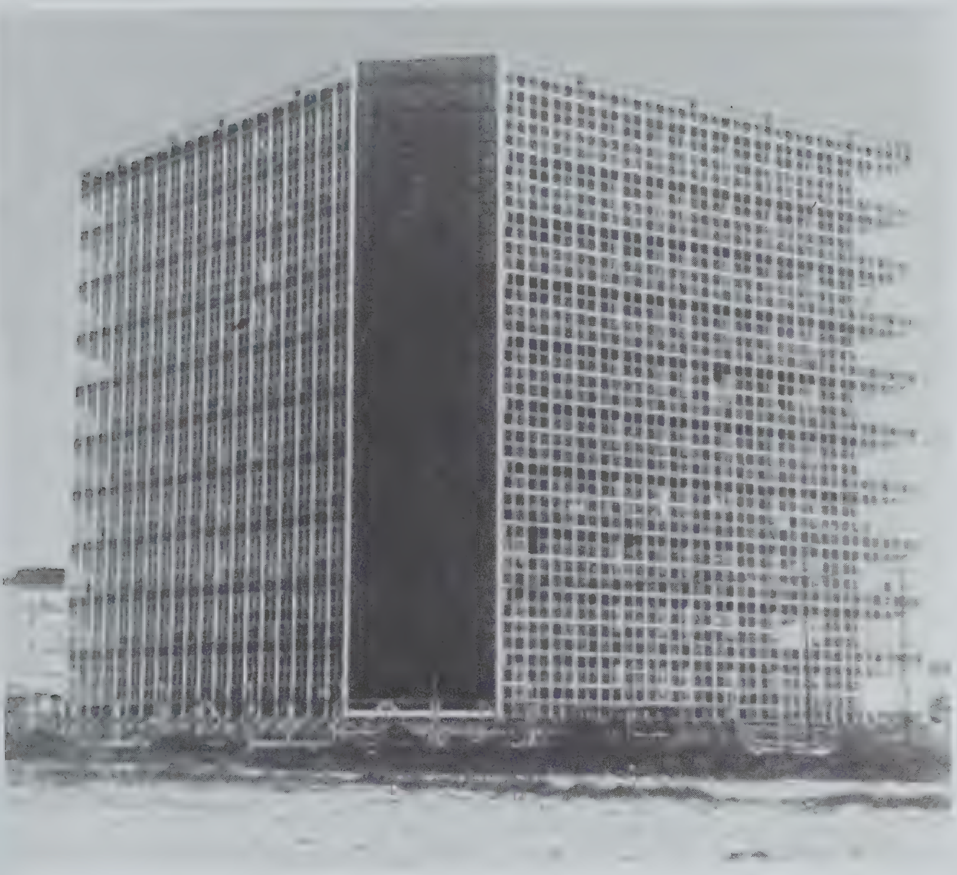


Figure 7. Orbassano apartment building

Table 3. Estimated Results for Orbassano

Month	Thermal Load without Passive Technology GJ	Thermal Load without Passive Technology MBtu	Estimated Thermal Load with Passive Technology GJ	Estimated Thermal Load with Passive Technology MBtu	% Energy Savings Compared to a Building with No Solar Technology
January	314	298	228	216	27.4
February	229	217	142	135	38
March	189	179	73	69	61.4
April	97	92	3	3	97
October	93	88	3	3	96.9
November	202	192	237	225	32.2
December	272	258	201	191	26.1
Year	1396	1324	787	842	43.6

Experimental data will be available next year.

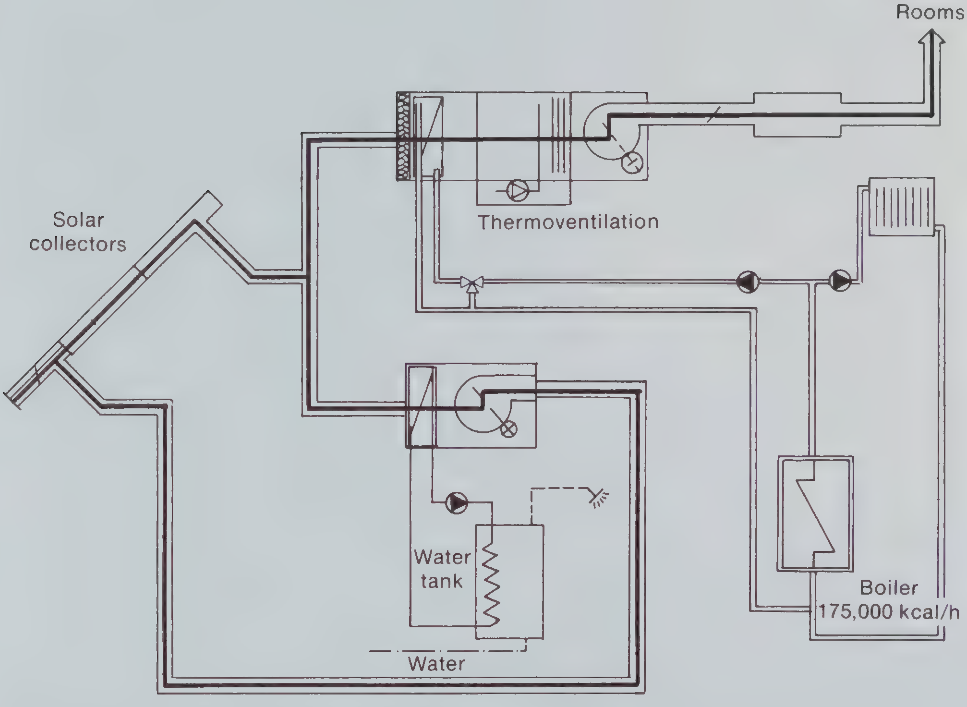


Figure 8. Orbassano apartment building, mechanical system - winter mode

MONCALIERI APARTMENT BUILDING

Location: Moncalieri
Latitude: 45°N
Degree-days: 2570°C-day (4630°F-day)
Date of Completion: 1984
Heated Volume: 12,000 m^3 (420,000 ft^3)
Number of Apartments: 42
Number of Floors: 7

Another interesting building in the same experimental program as the preceding one is located near Turin. This seven-story building has sunspaces integrated on all four sides. While some sunspaces on the south wall have fixed glazing, others have movable glazing that can be opened completely, transforming the sunspaces into balconies during the summer (Figures 9, 10, and 11). Small attached sunspaces on the three remaining sides of the building insulate the envelope. The designer estimates that 18.5% of the total thermal load will be met by the passive systems (see Table 4 for estimated results). All

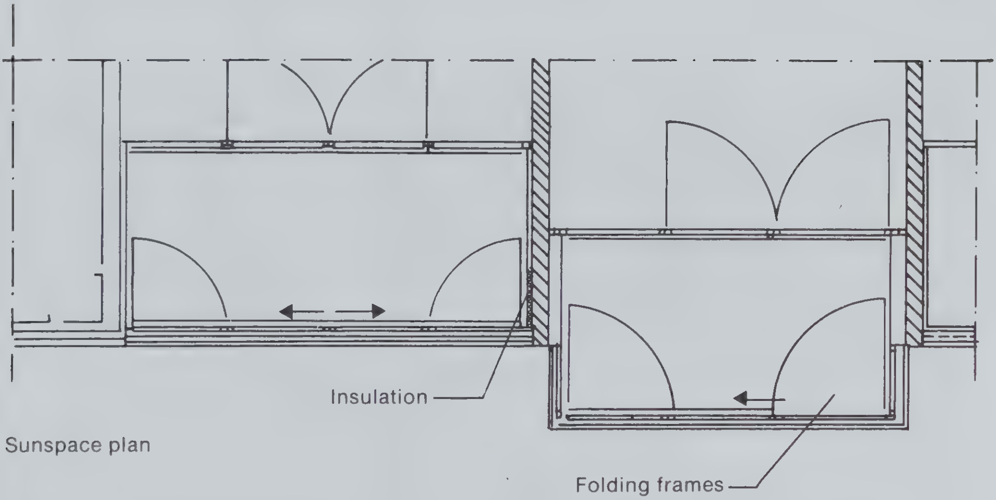


Figure 9. Moncalieri apartment building, sunspace plan

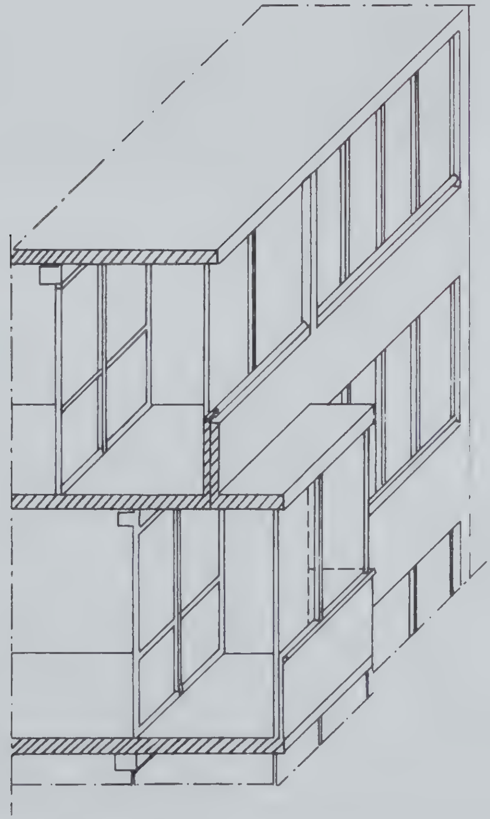


Figure 10. Moncalieri apartment building, sunspace axonometric

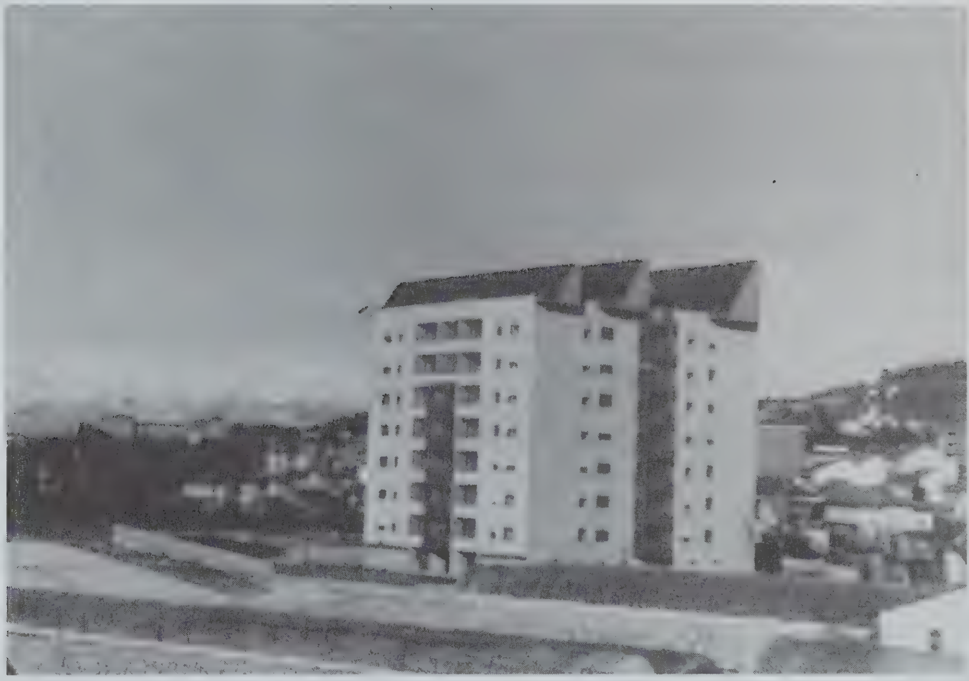


Figure 11. Moncalieri apartment building

Table 4. Estimated Results for Moncalieri

Month	Thermal Load without Passive Technology GJ	Thermal Load without Passive Technology MBtu	Estimated Thermal Load with Passive Technology GJ	Estimated Thermal Load with Passive Technology MBtu	% Energy Savings Compared to a Building with No Solar Technolog
January	358	340	251	238	30
February	361	343	160	152	39
March	216	205	72	68	66
April	110	104	15	14	86
October	107	102	33	31	69
November	235	223	158	150	33
December	310	294	227	215	27
Year	1697	1611	916	868	43

the walls are insulated with 6 cm (2.4 in.) of polystyrene. An active system consisting of 380 m^2 (4090 ft^2) of air collectors is mounted on the roof at a 55° tilt (Figures 12 and 13).

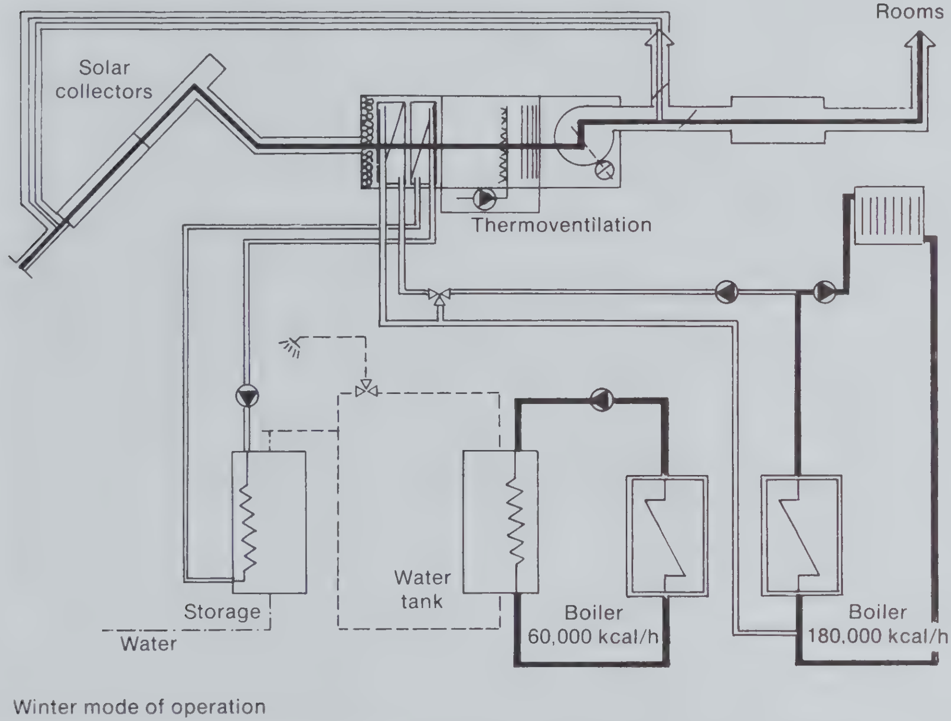


Figure 12. Moncalieri apartment building, mechanical system diagram

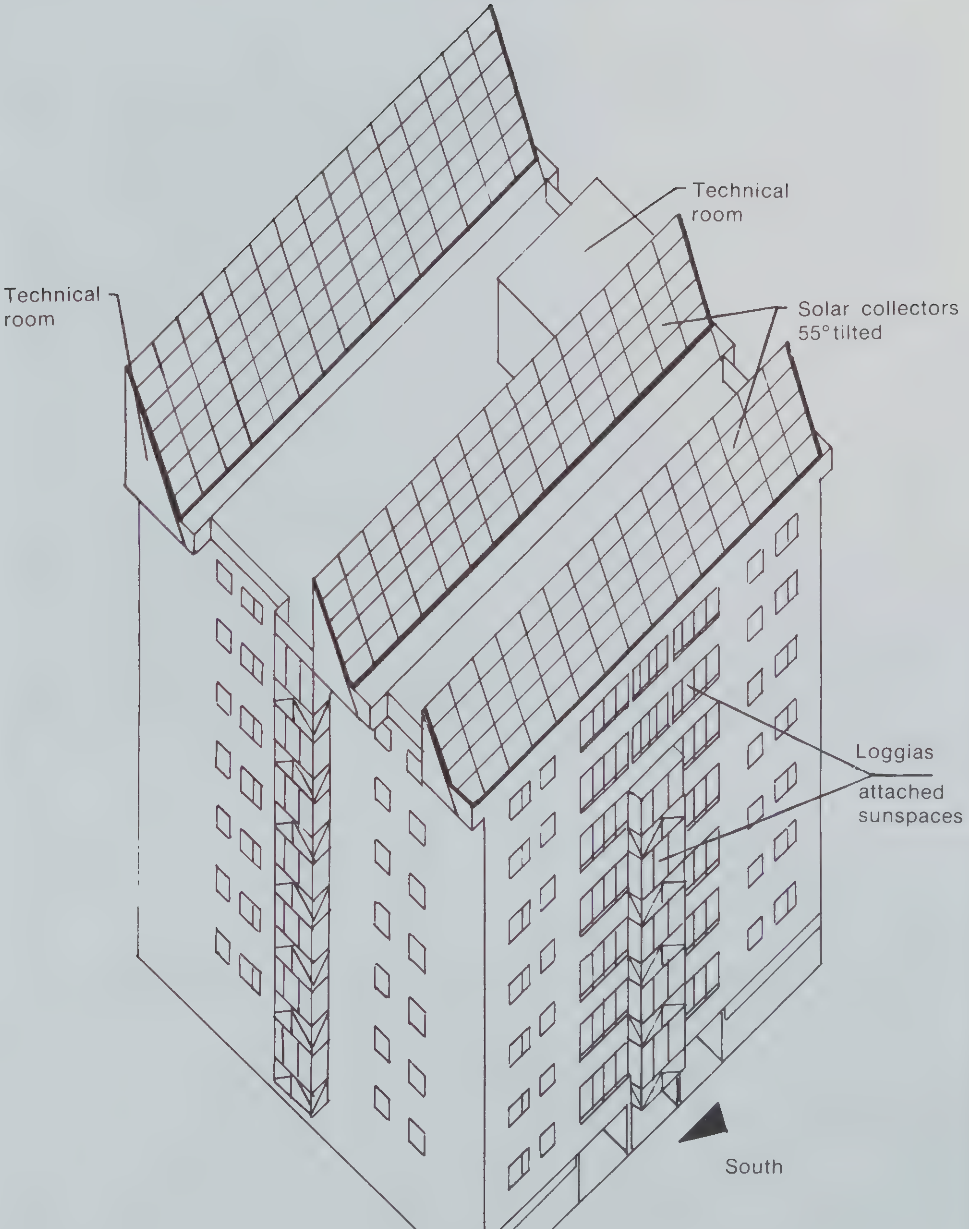


Figure 13. Moncalieri apartment building, axonometric

SALVIANO APARTMENT BUILDING

Location: Salviano
Latitude: 44°N
Degree-days: 1360°C-day (2450°F-day)
Date of Completion: 1982
Heated Volume: 6200 m^3 (220,000 ft^3)
Number of Apartments: 24
Number of Floors: 6

The main passive system for this apartment building is 600 m^2 (6500 ft^2) of 0.3-m-(1-ft-) thick brick Trombe walls (Figures 14, 15, and 16). The single glazed surface in front of the solar walls can be opened completely to allow cooling during the summer. Direct gain contributes to space heating via 300 m^2 (3200 ft^2) of double glazing. Both the passive components (Trombe wall and direct gain) have external PVC shutters; continuous balconies provide overhangs for summer shading. Domestic hot water is provided by 46 m^2 (490 ft^2) of water-heating collectors installed at a 40° tilt on the roof.

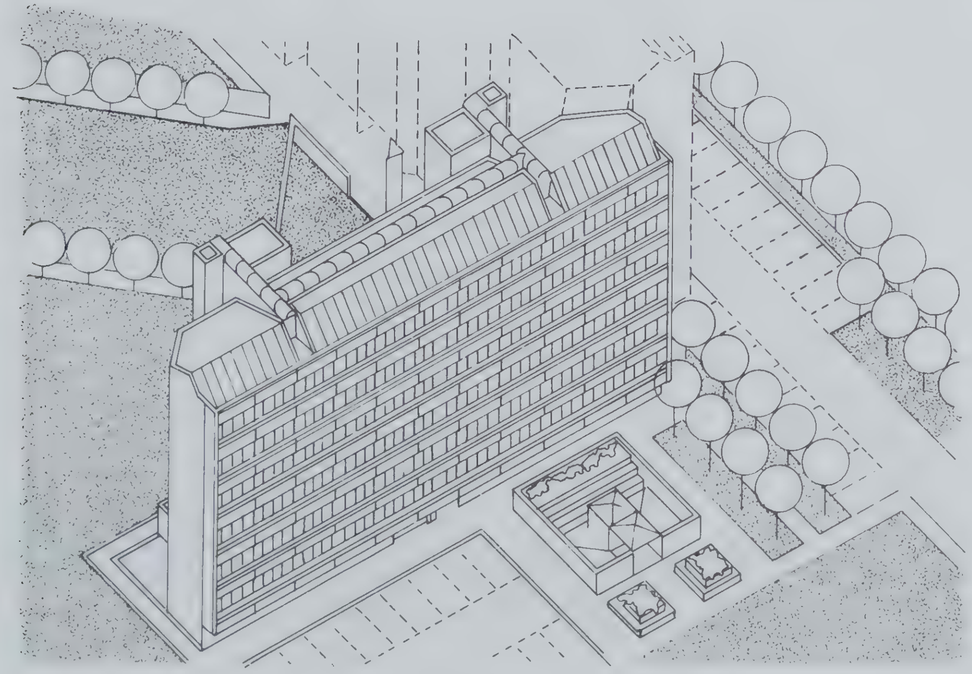


Figure 14. Salviano apartment building, axonometric

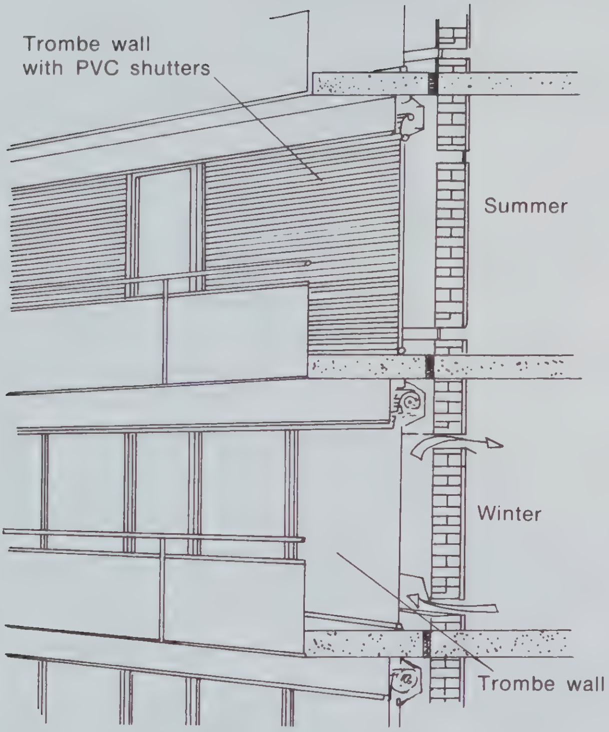


Figure 15. Salviano apartment building, Trombe walls

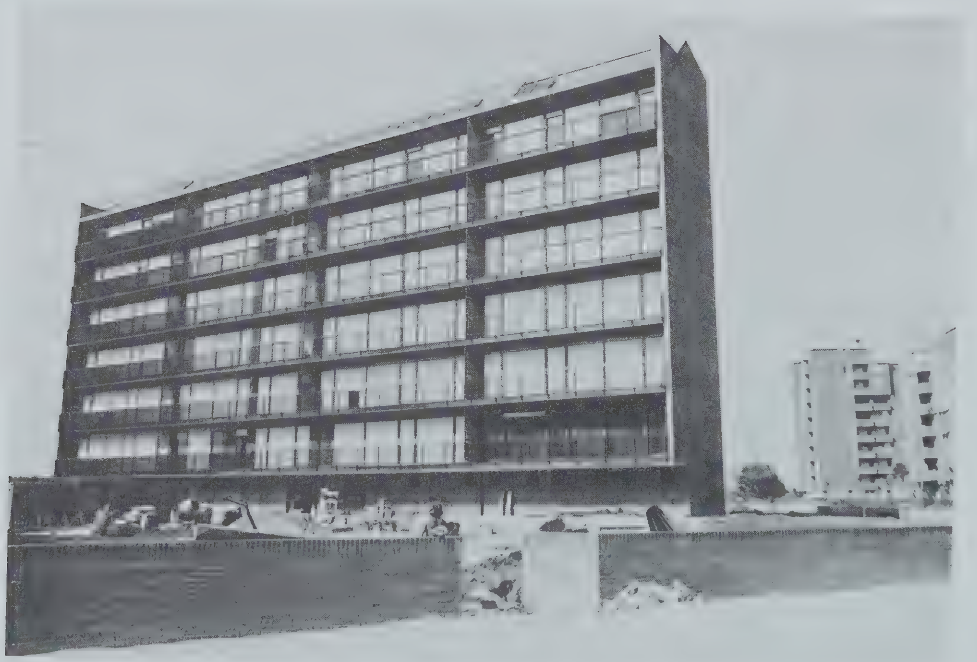


Figure 16. Salviano apartment building

This project, and the Carrara apartment building that follows, are part of the biennial (1978-1980) activity of the "Ten Year Plan for Housing" promoted by the local Tuscany Government. This is an experimental program for the construction of 27 multifamily buildings with different size apartments and different styles for various climates, using energy conservation as well as different passive solar systems. Some of these projects have been selected for a 1979 bilateral cooperation project of the Italian Ministry of Industry and the U.S. Department of Energy for the development of passive solar demonstration houses to be designed, built, and instrumented in Italy and the United States.

These two buildings are examples of a multifamily unit design used commonly in Italy; the units are long and narrow, have good southern exposure, and are suitable for integrating solar technologies.

CARRARA APARTMENT BUILDING

Location: Carrara
Latitude: 44°N
Degree-days: 1540°C-day (2770°F-day)
Date of Completion: 1981
Heated Volume: 6400 m^3 (230,000 ft^3)
Number of Apartments: 18
Number of Floors: 3

This interesting, three-story building is located near Pisa. A continuous sunspace is formed of 170 m^2 (1830 ft^2) of 60°-tilted, folding, single-glass panels that enclose all balconies on the south side (Figures 17 and 18). Because glazing covers the walls of the room facing the sunspace, the passive system provides direct gain heat when the sun's rays strike the internal windows, or isolated gain when the rays cross the external glass and strike the floor of the sunspace. External, movable, cloth blinds and the masonry overhangs (balconies) provide summer shade. An estimated 35% of the total thermal load is provided by the passive systems. For hot water, 190 m^2 (2040 ft^2) of 60°-tilted water collectors are integrated on the balconies' parapet.

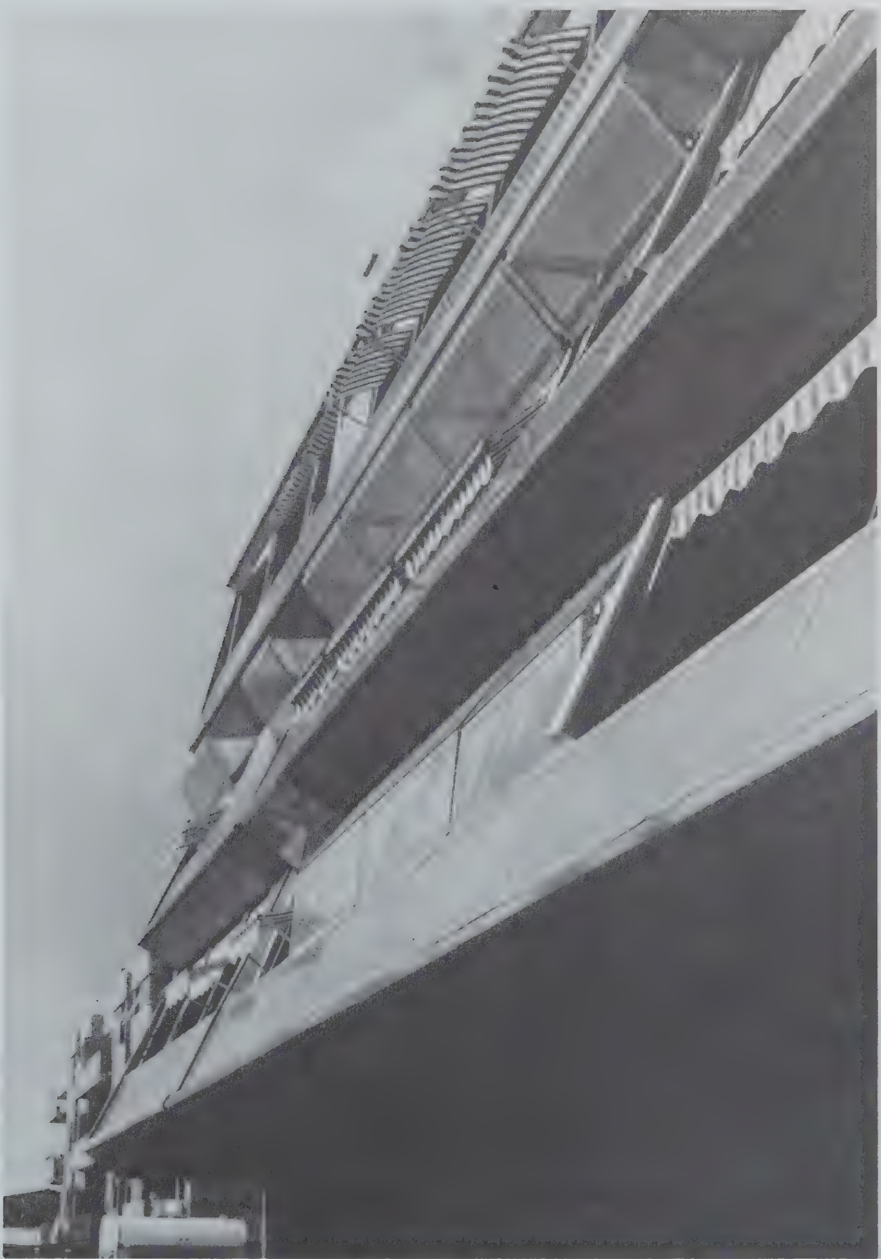


Figure 17. Carrara apartment building

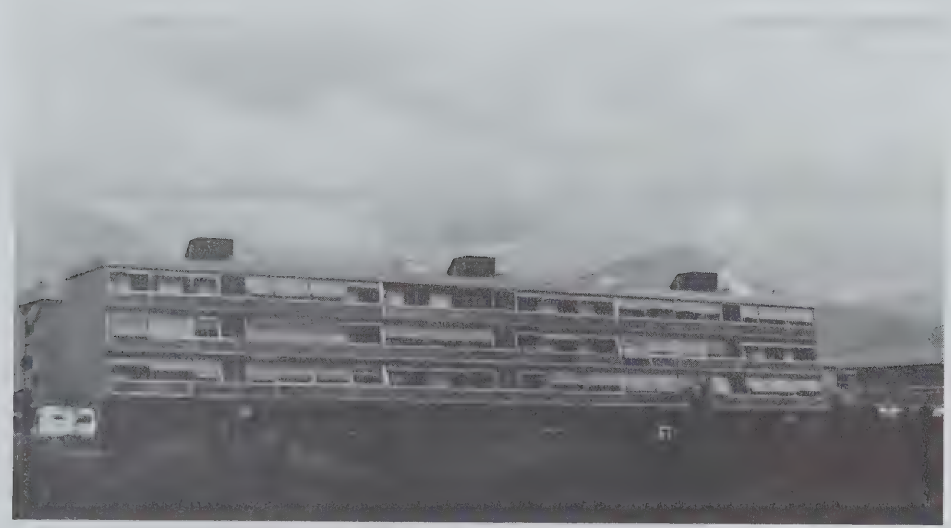


Figure 18. Carrara apartment building

CASIER HOUSE

Location: Casier (Treviso)
Latitude: 46°N
Degree-days: 2160°C-day (3890°F-day)
Heated Volume: 865 m^3 (31,600 ft^3)
Date of Completion: 1982
Number of Apartments: 1
Number of Floors: 2

Italy has only a few passive detached houses: only 10% of the passive construction is represented by single-family units. This small villa near Treviso is an attractive home that incorporates bioclimatic features (Figures 19, 20, and 21).

The two greenhouse surfaces are formed by 60 m^2 (650 ft^2) of vertical single glass plus 12 m^2 (130 ft^2) of 78°-tilted glass. The two-story greenhouse occupies two-thirds of the building's south side for a total heated volume of 200 m^3 (2200 ft^3). The glazed area is divided into windows, some of which can be opened to ventilate the adjacent rooms. The glazed area can be shaded from within with thick, white cloth blinds and from the outside by deciduous trees planted on the south side of the building.

A thick, 9-m^2 (100-ft^2) concrete wall, painted black, functions as storage and contributes to heating of the adjacent rooms. A portion of the earthen floor inside the greenhouse also serves as storage.

A fireplace is used as backup when passive systems cannot completely meet the thermal needs. A conventional heating system occasionally supplies the thermal load. The passive systems perform well enough to cover most of the heating needs of the family, even during the cold winter.

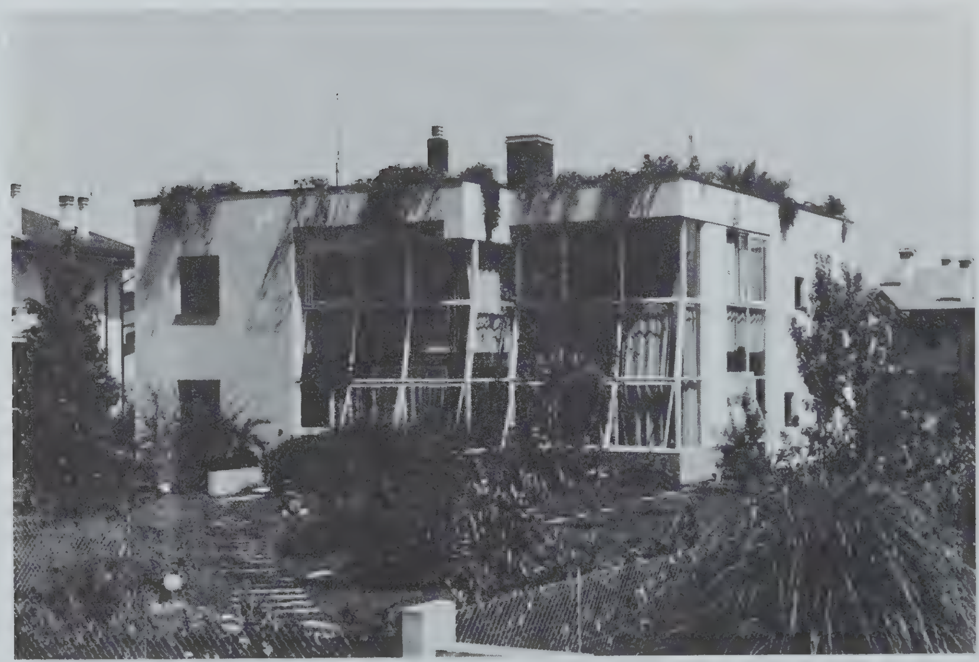


Figure 19. Casier house

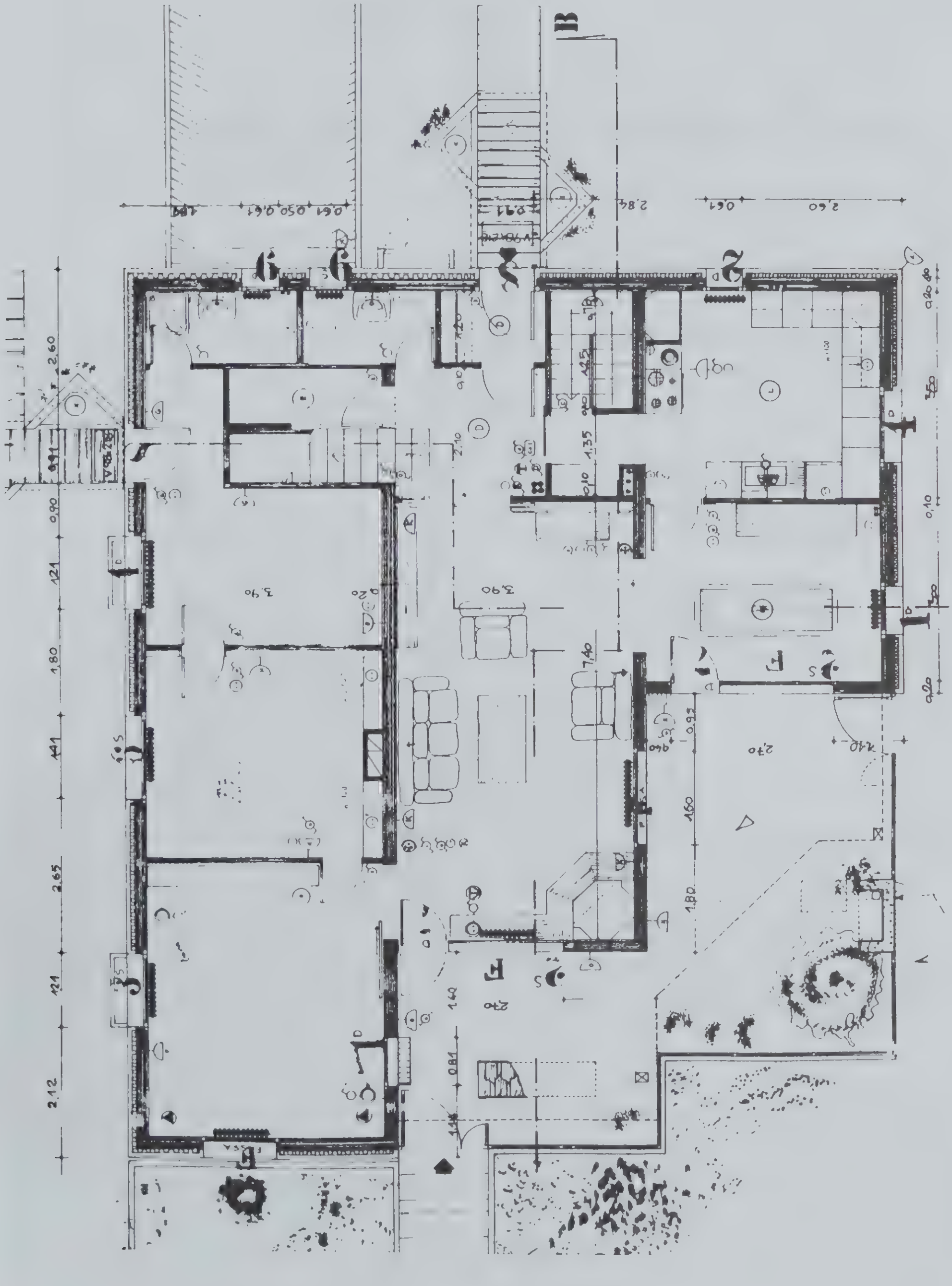


Figure 20. Casier house, ground floor plan

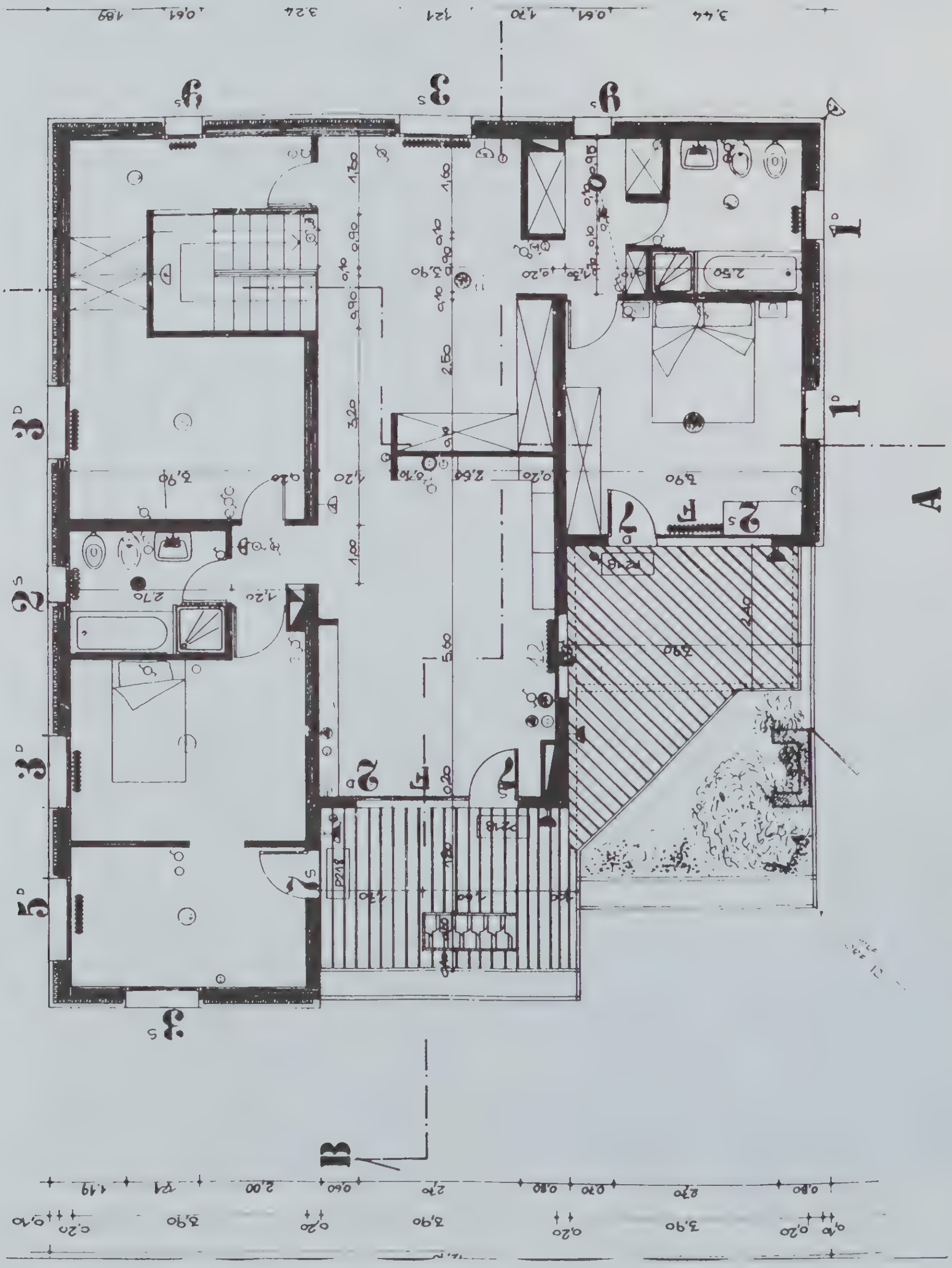


Figure 21. Casier house, first floor plan

CASALPALOCCO HIGH SCHOOL

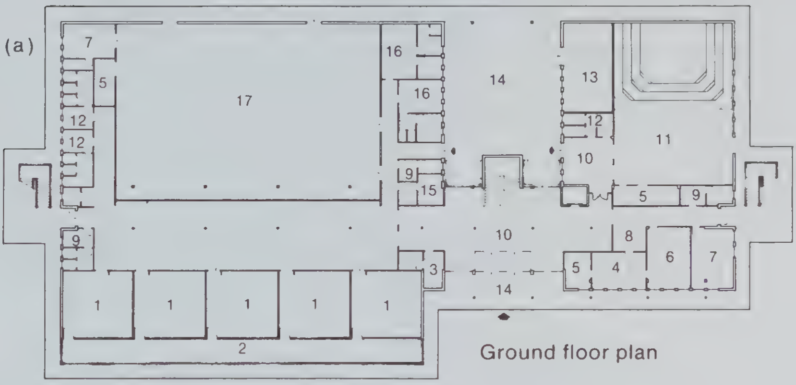
Location: Casalpalocco (near Rome)
Latitude: 42°N
Degree-days: 1440°C-day (2590°F-day)
Date of Completion: 1982
Heated Volume: 18,300 m^3 (646,000 ft^3)
Number of Floors: 3

This building, and the Castrovillari elementary school that follows, are two of the solar school buildings in Italy for which data are now accumulating. Demonstration programs and experimental schools have been under way since 1978 when the first school was designed near Venice. Passive solar schools have been built all over Italy, in particular: 4 nursery schools, 6 kindergartens, 3 elementary schools, 2 middle schools, and 4 high schools with a total volume of 170,000 m^3 (6 million ft^3). The passive systems for all 19 buildings perform well.

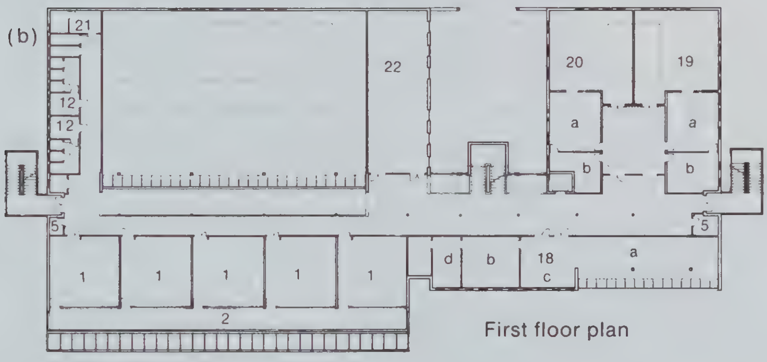
The Casalpalocco high school near Rome is a compact, rectangular building with a long east-west axis (Figures 22, 23, 24, and 25). Rows of sunspaces in front of the classrooms line the south side. A full-height atrium spans the north-south depth of the building. The main entrance doors and the stairways are in the atrium. Steel-framed clerestories on the north provide light and heat to spaces below. The clerestories also contain the parabolic concentrating collectors described below.

The attached sunspaces, which are the main passive system, contain 120 m^2 (1300 ft^2) of single glass and 250 m^2 (2700 ft^2) of 36°-tilted polycarbonate. The total sunspace floor area is 280 m^2 (3000 ft^2).

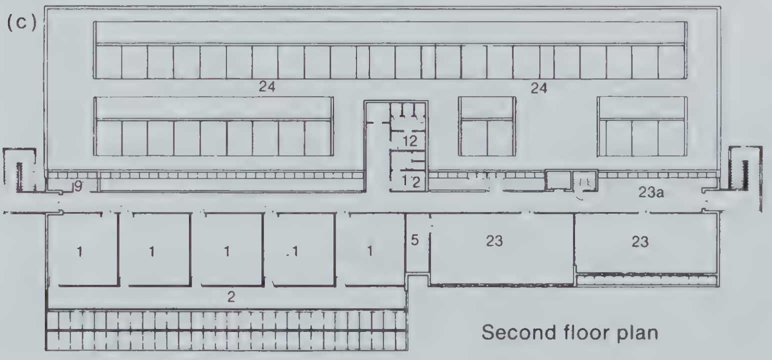
Navy blue venetian blinds cover the glass in front of the classrooms. These blinds protect the classrooms from glare and also collect solar heat, which is then transferred to the classroom by convection through the windows. Heat is also transferred through the masonry wall.



Ground floor plan



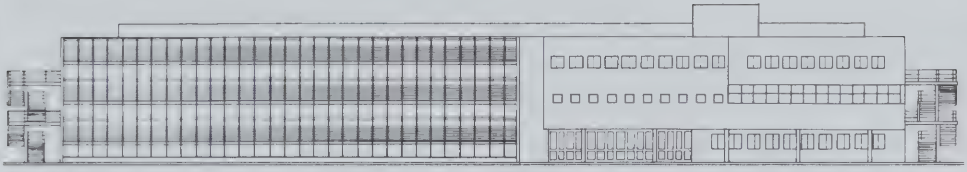
First floor plan



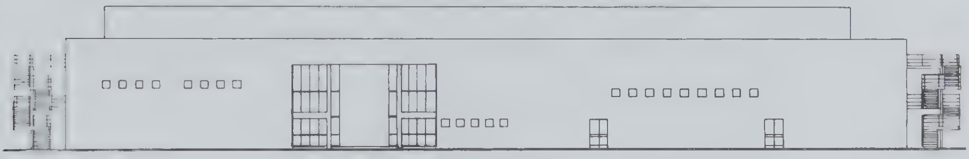
Second floor plan

1 Classroom
2 Sunspace
3 Porter
4 Offices
5 Depository
6 Headmastership
7 Teacher's room
8 Waiting room
9 Teachers' bathroom
10 Hall
11 Auxiliary activities room
12 Bathroom
13 Thermal power station
14 Porch
15 Physics laboratory
16 Dressing room
17 Gymnasium
18 Library
  a reading room
  b sound-and-video tape
  c catalogues
  d records office
19 Chemistry room
  a laboratory
  b teacher
20 Physics room
  a laboratory
  b teacher
21 Bathroom
22 Auxiliary activities
23 Drawing room
23a Exhibition area
24 Roof with solar collectors

Figure 22. Casalpalocco high school, a) ground floor plan, b) first floor plan, c) second floor plan



a) South elevation



b) North elevation

Figure 23. Casalpalocco high school, a) south elevation, b) north elevation

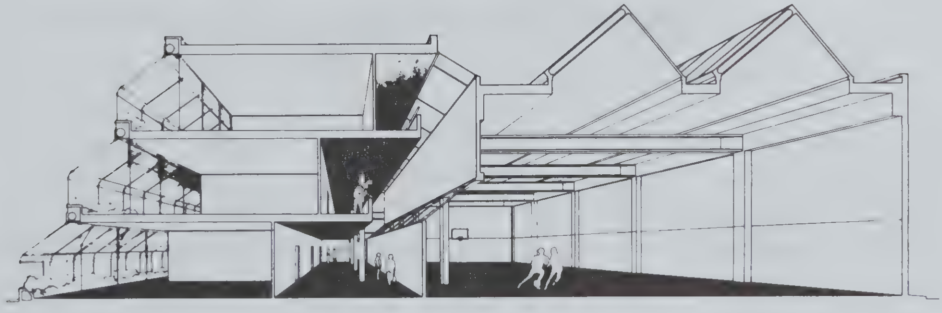


Figure 24. Casalpalocco high school, perspective

Finally, the building is superinsulated with respect to the standard required by Italian law, which specifies a maximum overall heat loss coefficient equal to 0.66 $\mathrm{W/m^3}$°C, while the building exhibits a value of 0.36 $\mathrm{W/m^3}$°C.

The building is passively cooled in the summer by shading the sunspaces with movable PVC blinds on the outside of the glazed surface. In addition, by opening a section of vertical glazing and vents at the bottom of the shutter casings, the occupants can have adequate ventilation.

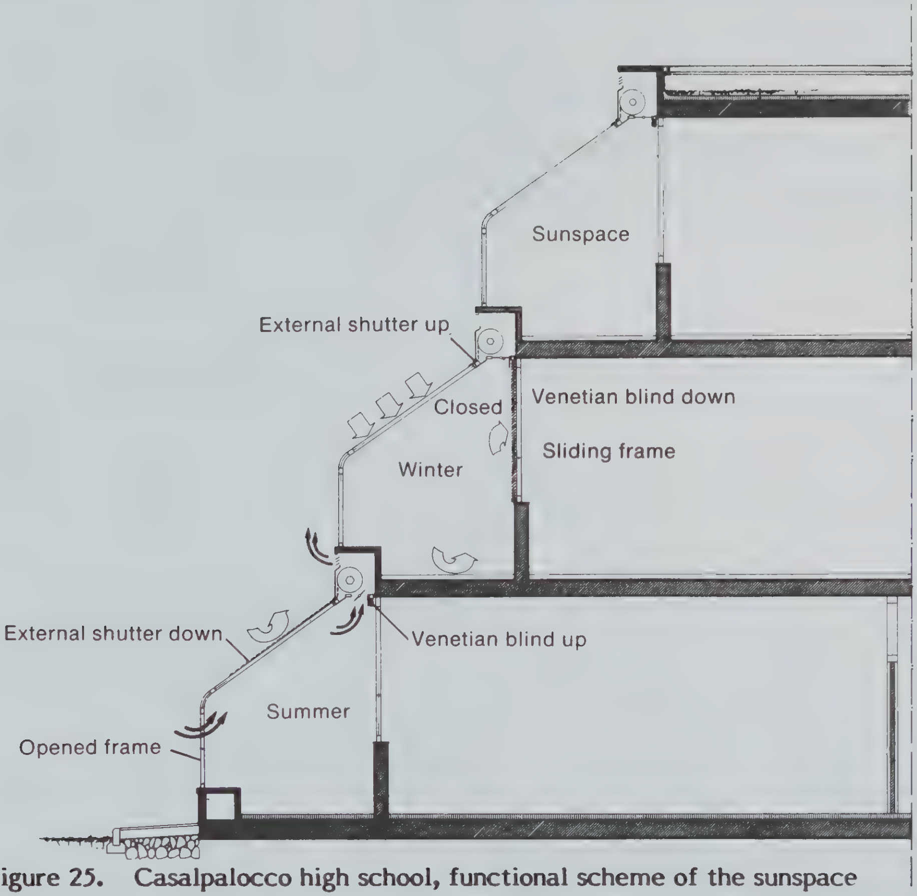
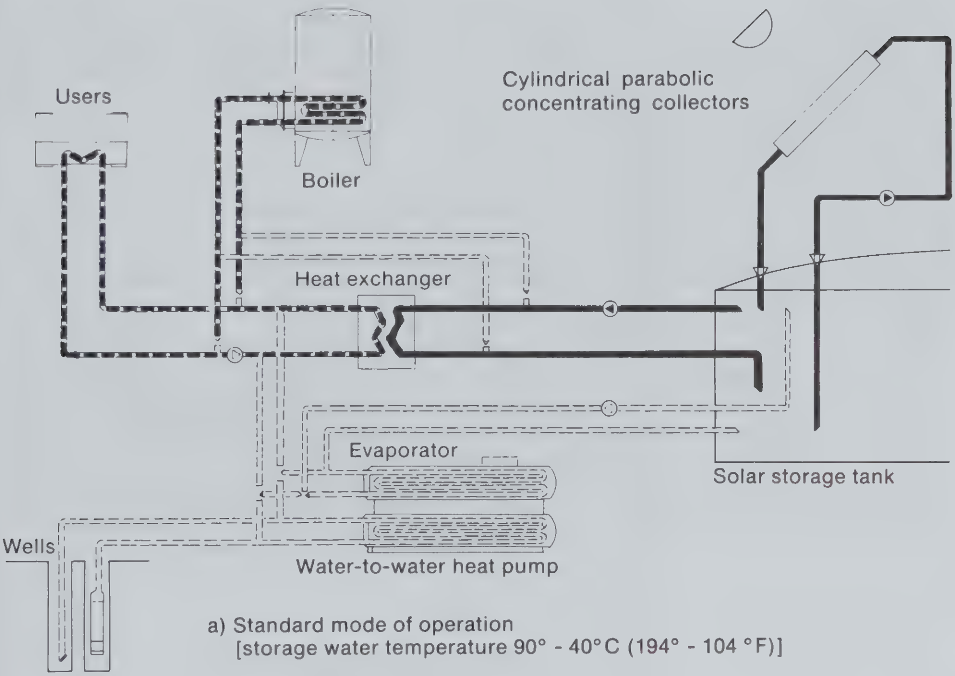


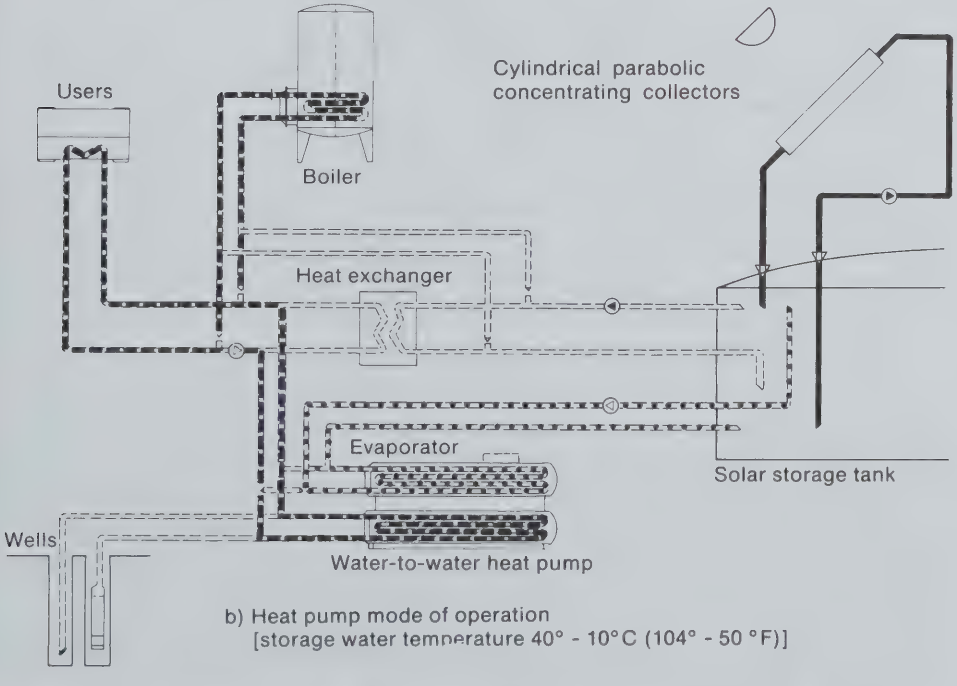
Figure 25. Casalpalocco high school, functional scheme of the sunspace

The active system consists of 250 m^2 (2700 ft^2) of concentrating parabolic cylinder collectors (40° tilt) coupled to an underground storage tank that contains 750 m^3 (198,000 U.S. gal) of water (Figure 26). Depending on the seasonal storage temperature, the active system operates in one of three modes:

> **Mode A:** [storage temperature between 90°C (194°F) and 40°C (104°F)]. Heat is transferred from the solar collectors to the storage tank. A heat exchanger connects the tank to the heating units and to a hot water boiler, which provides the daily domestic hot water supply.
>
> **Mode B:** [storage temperature between 40°C (104°F) and 10°C (50°F)]. Heat from the storage is upgraded by a water source heat pump and distributed to the boiler and the heating units.



a) Standard mode of operation
[storage water temperature 90° - 40°C (194° - 104 °F)]



b) Heat pump mode of operation
[storage water temperature 40° - 10°C (104° - 50 °F)]

Figure 26. Casalpalocco high school, functional scheme of the solar plant, a) standard mode of operation, b) heat pump mode of operation

Mode C: [storage temperature below 10°C (50°F)]. In this mode, heat cannot be extracted from the storage. Instead, the heat source for the heat pump consists of underground aquifier water at 15°C (60°F).

The school's annual energy requirement is 46 GJ (44 MBtu) for domestic hot water and 360 GJ (341 MBtu) for space heating—a total thermal load of 406 GJ (385 MBtu)/yr.* Passive systems provide 47.8% of the space heating load; that is, 172 GJ (163 MBtu)/yr through sunspaces and direct gain from the south windows and the clerestories. Active systems (solar collectors, heat pump, seasonal storage) provide the remaining 52.2% plus all the domestic hot water load, for a total of 234 GJ (222 MBtu)/yr.

CASTROVILLARI ELEMENTARY SCHOOL

Location: Castrovillari (near Cosenza)
Latitude: 39°N
Degree-days: 1020°C-day (1840°F-day)
Date of Completion: 1982
Heated Volume: 1500 m^3 (53,000 ft^3)
Number of Floors: 1

The elementary school was designed for the small town of Castrovillari (southern Italy, near Cosenza). The entrances and the offices of the school are on the north; the classrooms face south for optimum year-round exposure to the sun (Figures 27 and 28). Heating is provided by 170 m^2 (1800 ft^2) of Barra-Costantini solar walls. In these thermosiphon air panel systems, the solar absorber has a small heat capacity and is separated from the south wall of the building with a layer of insulation to maximize the heat exchange between the absorber and the air. Heat is transferred northward into the building by airflow through channels in the ceiling. The rooms are heated directly by the warm air and indirectly by radiation from the warm ceiling. The massive ceiling provides thermal storage.

The solar walls of the school work in different ways, depending on the season and the time of the day.

---

*$M = 10^6$, $G = 10^9$

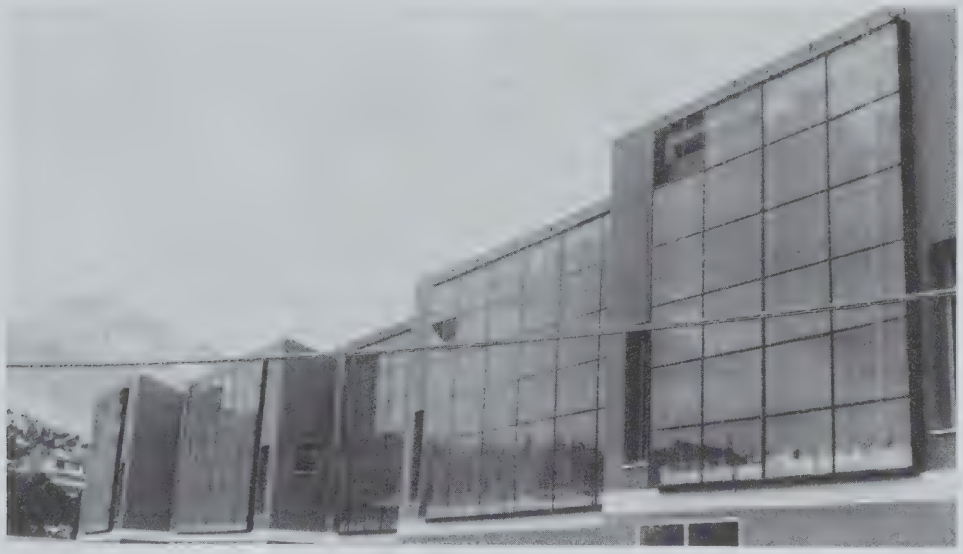


Figure 27. Castrovillari elementary school

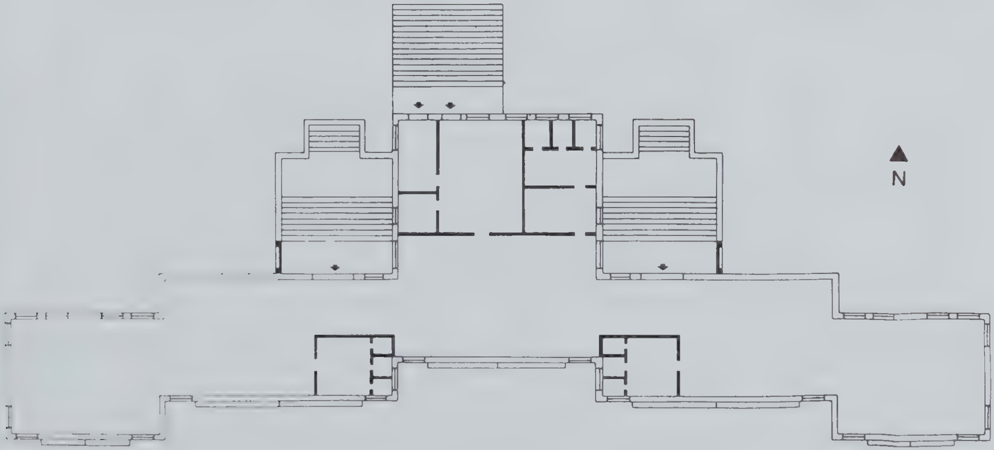


Figure 28. Castrovillari elementary school, plan

Winter day operation: the dampers for air circulation control are kept open. The air heated in the solar collectors flows through the ceiling air channels into the north sides of the classrooms, and from there is drawn back again into the collectors. While flowing through the channels, some of the heat is transferred to the ceiling concrete and stored there; the remaining heat goes directly to the rooms.

Winter night operation: all dampers are closed to prevent reverse air circulation. The heat previously stored in the walls and ceiling radiates into the rooms.

Summer day operation: the outside vents are open; the inside dampers are closed. The heat from the solar collectors is allowed to vent to the outside through convection. Fresh air can be drawn into the lower part of the collectors either from outside or inside (i.e., from the north side of the school).

Summer night operation: the outside vents are kept open. Air circulation starts (if the outside temperature is lower than the inside) and can cool the ceiling storage. No overheating problems exist even during very hot days.

Because of the good climatic conditions and the high efficiency of the thermosiphon air panel systems, the school is almost self-sufficient in terms of its energy needs.

CONCLUSIONS

A new energy design attitude is emerging in Italy with the increasing use of energy-conserving features. Many traditional architectural elements such as materials and components using heavy mass, shading devices, and different kinds of thermal shutters, are now being used to enhance a building's energy efficiency. Other architectural elements such as balconies and loggias are being adapted to serve as passive components.

Careful analysis of the performance and economic data generated by these existing buildings will help us to produce guidelines for a more mature generation of passive solar buildings. To that end, experimental data on many projects are being gathered and studied.

REFERENCE

Funaro, G., A. Fanchiotti, and E. D'Errico, 1985. *116 Edifici Solari Passivi in Italia*. Rome: National Committee for Nuclear and Alternative Energies. (In Italian.)

Passive Solar Journal, 3(3), 321-323 (1986)

Book Review

The Sunspace Primer — A Guide for Passive Solar Heating

R. W. Jones and R. D. McFarland. New York: Van Nostrand Reinhold Co.,
1984. 301 pp. ISBN 0-442-24575-0. Hardbound. $32.50.

This delightful volume, published in 1984, should be on the shelves of every architect, designer, homebuilder, and developer who wants to know how to design and estimate the performance of the sunspace, "solar greenhouse," or solarium. Sunspaces represent one of the best markets for passive solar design today, and this book provides essential design information. What's more, *The Sunspace Primer* also gives well-prepared, basic passive solar design information as an extra bonus.

Organized into eight chapters, plus a concise appendix, this book is packed with the latest, most simplified design aids based on recent research. It begins with a complete review of passive solar heating systems, discussion of important conservation (thermal integrity and insulation) requirements, and sources of more information.

Solar energy resources and their estimation are reviewed in a way that is understandable to nonmeteorologists (a rare occurrence indeed). The topic of windows and glazings is well covered as are heat storage systems design, materials, and construction. A simplified discussion of why heat storage is necessary debunks myths and misinformation that abound in the passive solar field today.

The chapter on Conservation is fairly well written and helps explain the necessity for balancing conservation and solar energy for optimum performance and comfort.

It is unfortunate that the chapter on Conservation focuses rather narrowly on the typical "R-value," steady-state approach to envelope conservation, since the rest of the book is so good. The role of "free mass" in heavy exterior walls is not touched upon. This may be because the Los Alamos "solar load ratio" method used for performance estimates is based on steady-state input data and assumptions about light, medium, and heavy construction including the effect of mass.

Some of the best materials in the book are contained in the two chapters on Distribution and Controls. It is here that a passive solar design can succeed or fail. Included is discussion of mass to control overheating, fixed vs. movable overhangs and shading, ventilation and glazing angle, and site orientation issues. This chapter uses simple terminology, provides tables on "rules of thumb," and gives examples.

The final chapter on Evaluation provides updated SLR methods to estimate the performance of the sunspace design. Interesting maps, performance calculations, and work sheets aid the user in finding expected performance levels.

All chapters include references and bibliography materials to assist the user in obtaining more information. The appendices provide more worksheets and methods to support fairly complete analysis using the book.

Despite some simplification and minor editing problems, *The Sunspace Primer* is one of the best books on passive design out today, and the only book now available that treats sunspace design in an integrated package. A job well done.

Reviewed by Bion D. Howard
National Association of Home Builders
Washington, D.C. 20005

This review has been adapted by Bion Howard from a review that originally appeared in *Concrete Masonry Solar Architecture Quarterly*, published by the National Concrete Masonry Association.

Passive Solar Journal, 3(3), 325-326 (1986)

About the Contributors

J. Douglas Balcomb is a Distinguished Research Fellow at the Solar Energy Research Institute, on leave of absence from the Los Alamos National Laboratory. He is recipient of the ASES Passive Pioneer Award in 1984 and Charles Greeley Abbott Award in 1985 to honor his role "as foremost contributor to the development of passive solar calculations."

Gabriella Funaro received her architecture degree from New Mexico State University. She is now a research architect with ENEA, the National Committee for Nuclear and Alternative Energies, near Rome. Her recent work has included a survey of passive solar architecture in Italy.

Bion D. Howard is Manager of Mechanical Systems and Energy Programs for the National Association of Homebuilders in Washington, D.C. His current work focuses on energy-efficient residential construction methods and monitoring codes and standards. His previous affliations include the National Concrete Masonry Association and the U.S. DOE National Solar Data Program. He is a member of the ASES Board of Directors.

Dallas D. Hill is a Mechanical Engineer at the National Bureau of Standards where he does building heat transfer experiments. He received his MS at Colorado State University in 1985.

Allan T. Kirkpatrick is Associate Professor of Mechanical Engineering at Colorado State University. He received his Ph.D in 1981 from the Massachusetts Institute of Technology. He has done research in heat transfer in buildings for 6 years, and his current research concerns natural convection in passive solar buildings.

Donald A. Neeper is a Staff Member in the Solar Energy Section of Los Alamos National Laboratory. He has been involved in the analysis of solar energy applications to buildings for 8 years. His current activities include the analysis of advanced thermal transport and storage concepts for passive and hybrid solar systems.

Kirk W. Stokes is a Mechanical Engineer at the New Mexico Solar Energy Institute in the field of photovoltaics. He received his MS in Mechanical Engineering from Colorado State University in 1986.

BOSTON ARCHITECTURAL CENTER
LIBRARY
320 NEWBURY ST.
BOSTON, MA. 02115

CODEN: PASJDF 3(4) i-iv, 327-448 (1986)
ISSN: 0277-6456

Passive Solar Journal

Volume 3, Number 4, 1986

LIBRARY
BOSTON ARCHITECTURAL CENTER

Includes Indexes to Volume 3

Heating, Cooling, and Lighting for Buildings

PASSIVE SOLAR JOURNAL

Sponsorship. *Passive Solar Journal* is the official journal of the Passive Architecture and Construction Division of the American Solar Energy Society, Inc.

Indexing and Abstracting Services. Articles published in *Passive Solar Journal* selectively appear in all major indexing and abstracting publications.

Manuscript Preparation and Submission. See inside back cover.

Subscription Information. *Passive Solar Journal* (ISSN: 0277-6456) is published in four numbers by Marcel Dekker, Inc., 270 Madison Avenue, New York, New York 10016. The subscription rate for Volume 3 (1986), is as follows:

Non-Member Institutions	$ 125.00
Society Member Institutions	90.00
ASES Membership Dues	150.00
Non-Member Individuals	47.50
Society Member Individuals	25.00
ASES Membership Dues	50.00

Your order must be prepaid by personal check or may be charged to MasterCard, VISA, or American Express. Please add $12.00 for surface postage outside the United States. For airmail to Europe, add $15.00; to Asia, add $19.00. Please mail payment with order to: Marcel Dekker, Inc., P. O. Box 11305, Church Street Station, New York, New York 10249.

Copyright © 1987 by Marcel Dekker, Inc. All rights reserved. Neither this work nor any part may be reproduced or transmitted in any form or by any means, electronic or mechanical, microfilming and recording, or by any information storage and retrieval systems without permission in writing from the publisher.

Authorization to photocopy items for internal or personal use, or the internal or personal use of specific clients, is granted by Marcel Dekker, Inc. for users registered with the Copyright Clearance Center (CCC) Transactional Reporting Service, provided that the base fee of $3.50 per copy is paid directly to CCC, 27 Congress Street, Salem, MA 01970. For those organizations that have been granted a photocopy license by CCC, a separate system of payment has been arranged. The fee code for users of the Transactional Reporting Service is: 0277-6456/86$3.50.

Contributions to this journal are published free of charge.

Passive Solar Journal

Official Journal of the Passive Architecture
and Construction Division of the
American Solar Energy Society, Inc.

LIBRARY
BOSTON ARCHITECTURAL CENTER

Editor-in-Chief

ROBERT W. JONES
Los Alamos National Laboratory
Mail Stop J577
Los Alamos, New Mexico 87545

Managing Editor

NANCY S. REECE
Solar Energy Research Institute
1617 Cole Boulevard
Golden, Colorado 80401

Consulting Editor

JEFFREY COOK
Arizona State University

Associate Editors

DENNIS A. ANDREJKO
State University of New York

J. DOUGLAS BALCOMB
Los Alamos National Laboratory

SUBRATO CHANDRA
Florida Solar Energy Center

EUGENE CLARK
Trinity University

MICHAEL J. HOLTZ
Architectural Energy Corp.

BION D. HOWARD
National Association of Home Builders

BRUCE D. HUNN
University of Texas

DONALD A. NEEPER
Los Alamos National Laboratory

CLAUDE ROBBINS
Architectural Energy Corp.

RICK SCHWOLSKY
Grafton Builders

ROBERT O. SMITH
Robert O. Smith & Associates

AIMS AND SCOPE

The **Passive Solar Journal** is the official journal of the Passive Architecture and Construction Division of the American Solar Energy Society, Inc., the United States Section of the International Solar Energy Society. This organization has sponsored major national and international passive conferences. The **Journal** is guided by a distinguished editorial board, an international panel of advisors, and expert peer reviewers.

The purpose of the **Passive Solar Journal** is to stimulate and support the flow and exchange of research and professional information. The **Journal** is intended to become the archival record and the standard international reference for the field, with principal directions and issues documented in illustrated and referenced presentations. Annual indexes provide detailed cross-reference access. The **Journal** contains full-length articles, book reviews, and opinions that meet the highest standards of verbal and graphic communication. The scope of subject matter is passive solar heating, passive cooling, and natural lighting plus related subjects including the following:

Advanced concepts
Building climatology
Codes and standards
Community planning
Component design
Computer methods
Conservation
Construction details
Control systems
Daylighting
Design tools
Direct gain
Domestic hot water
Earth coupling
Economic analysis
Education
Energy budgets
Energy storage
Evaporative cooling
Historical examples
Hybrid systems
Indirect gain
Indoor air quality
Instrumentation
Integration and optimization
Landscaping
Lifestyles and needs
Market development
Movable insulation
Phase change materials
Photovoltaic interface
Radiation resources
Retrofits
Roof ponds
Selective surfaces
Shading
Simulation
Sky radiation
Solar architecture
Solar greenhouses
Sunspaces
Testing and monitoring
Thermal comfort
Thermal networks
Thermosiphons
Trombe walls
Underground climate
Urban design
User evaluation
Ventilation
Window systems

Passive Solar Journal

Volume 3, Number 4, 1986

Contents

Editorial

Remembering John Yellott 327
R. Jones

Opinion

Solar Design: A Holistic View 329
R. Crowther

Passive Solar in the United States: 1976-1986 333
J. D. Balcomb

Daylighting in the Mt. Airy Public Library 349
M. Adegran, B. Andersson, and W. Place

The Performance of Adobe and Other Thermal Mass Materials in Residential Buildings 387
D. Robertson

A Passive Florida House 419
H. Beatty

Book Review

Concepts and Practice of Architectural Daylighting 435
V. Cartwright

About the Contributors 439

Author Index to Volume 3 441

Subject Index to Volume 3 443

Collective Contents to Volume 3 445

Passive Solar Journal, 3(4), 327 (1986)

Editorial

Remembering John Yellott

The passing of John Yellott last December sent shock waves through the solar energy research community. The impressive length and scope of John's career make it hard to think of an area not influenced by his work. We decided that an appropriate response would be a special issue of the *Passive Solar Journal* dedicated to the memory of John. This issue will be a collection of research and review articles on subjects related to his diverse interests and accomplishments.

In my recent conversations with many of John's friends and associates, I am struck by the astonishing range of his ideas and achievements and by how freely he shared himself with others. In a world often plagued with apathy, the care that John demonstrated toward his work and the people around him serves as an inspiration for all of us. His generosity is echoed in the willingness of his colleagues to contribute to this special issue. I am expecting articles on several subjects including roof ponds, thermal comfort, fenestration, and evaporative cooling. Although I wonder how one issue can do justice to the wealth of material, we will do our best to make it a fitting tribute to John.

I regret that assembling the special issue will take a few months; we foresee publication in August. Meanwhile, on behalf of the *Journal* editors and authors, I hereby dedicate the current issue as well to John's memory.

RW Jones

Robert W. Jones
Editor-in-Chief
Passive Solar Journal

Passive Solar Journal, 3(4), 329-332 (1986)

Opinion

Solar Design: A Holistic View

Richard L. Crowther
401A Madison St.
Denver, Colorado 80206

The sun's energy is the vitalizer and sustainer of life on our earth; it is reasonably predictable, though intermittent, and is our most pervasive nonpolluting energy source. Yet, solar energy applications have failed to sustain the missionary zeal of the past decade. During the middle and late 1970s solar technologies were in the spotlight of public interest. Solar technologies represented an ethic of vitality, a rapport with the radiant energy of the sun, and an answer to escalating energy cost. It appeared that solar would forever be part of the mainstream of architecture.

At present, the perverse use of our scientific and technological powers to create products, buildings, and systems that rely on nonrenewable nuclear and fossil fuels has us sliding into an abyss. As our local and global environment suffers devitalization, we are debilitated, and our contaminated air, water, and food perpetuate a decline in well-being. Our society is becoming ever more fragile and depleted. But our resiliency, ingenuity, and adaptability can be reemployed for recovery and rejuvenation.

Our expanding population puts an increasing demand upon the finite and polluting energies that now support our industries and way of life. We become pawns to the functions and physical aspects of the design of our homes and buildings, transportation vehicles, products, and systems. We are programmed to their convenience and servants to their prescribed functions. To an extent we become liberated by the leverage of the design, but also enslaved to its idiosyncracies.

On a global scale we put our existence at risk as we conceptualize, design, and construct. In designing programs, systems, or structures we incur the energy expenditure inherent in the materials and construction, after which we have to add the energy expenditure that will prevail for the lifetime operation and maintenance of the product or building. A vital consideration in the resource and energy equation should be the final disposition of the waste products and obsolete components of our designs. Recycling, reforming, and recovery of viable elements are projections that should attend initial design considerations.

Design is the powerful determinant of our lives. It dictates our sociological, psychological, and physical paths and limits. We spend about 90% of our time within the enclosures of homes, buildings, and motor vehicles. Our thinking and our activity are limited by the design of these indoor enclosures. We are further programmed by the features of the design. Where we put doors, windows, stairways, and light switches in buildings determines our behavioral response. Interior furnishings further limit our patterns of choice. Furniture creates limited pathways in space, and our sensory responses are conditioned by light, form, color, texture, and relative visibility of objects. In vehicles responsive operation is determined by the location and design of controls.

Every time we select certain criteria in planning and design, we establish certain opportunities and limitations. The well-being of our minds and bodies, our parameters of stress and stress release, and the factor of time are embodied in design.

The scope of holistic design includes all of the elements of physics, biology, and behavior. The physical elements of nature (sun, air, earth, and water), the conceptual and energy resources of humankind, our local ecology, and our biological and behavioral proclivities are all interdependent, interrelated, and interresponsive in terms of holistic planning and design. Every choice and option we exercise in design affects our local and global environment and the opportunities of wellness and survival.

The systems of nature and of humankind should be coincident and intersupportive. The regenerative and recuperative powers of nature should not be at odds with our human objectives. We need a higher level of science to maintain the sensitive balance. Our own predispositions and attributes need to be sympathetically and constructively aligned with the workings of natural order.

Only by holistic design can we optimize function, vitality, and health; minimize construction, interior, and landscape costs; and maximize self-sufficiency and sustainability in architecture or product design. Only by holistic design can material and labor costs be most effectively budgeted in light of energy implications, and life duration of the architecture or product be most appropriate and require the least off-site or nonrenewable energy demand.

Within the context of our contemporary life, localized, self-sufficient, and self-sustaining communities are the answer to greater vitality, personal freedom, health, and survivability. At the scale of the community we can handle the matters of economic and personal relationships, stewardship of resources and energy, holistic education, cooperative opportunities, and constructive endeavors. The more closely knit a community is, the more likely are we to avoid dissidence, crime, and violence. By encouraging nurturing and structuring within solar communities our national transiency would be reduced and opportunities within the community would encourage personal value and meaning.

The sun's energy is preeminent, and when coupled with other natural energies that are present everywhere, can be applied to a host of regenerative and productive uses. As we introduce other forms of natural energy sources such as wind, wave motion, and ocean and geothermal temperature gradients, we find that we have formidable localized on- and near-site energies that we can effectively use to free ourselves partially or totally from the fragility and tenuousness of centralized energy sources and elaborate distribution systems. Our present debacles and quandaries can only be moderated and abated by a new way of thinking and doing. For significant freedom we need breathable air, drinkable water, a livable earth, and self-sufficiency.

Our freedom and sustainability can be augmented by a broad base of solar applications, namely, daylighting, space heating, domestic water heating, convective cooling and ventilation, interior convection, humidification and dehumidification, thermal and photovoltaic electric conversion, water distillation, absorption and desiccant cooling, bioconversion, and drying of food and other products. Architectural sunspaces, atria, and attached greenhouses not only contribute to delight, health, and useful space, but can deliver passive solar heat as well.

Despite the current ebb of public zeal, we still need the sun as a fundamental energy source for our homes and buildings. Our advancing science and technology aligned with a natural order, characterized by the sun, should be a primary consideration in planning and design. Solar is basic to the regeneration of our ecological and economic vitality.

Passive Solar Journal, 3(4), 333-347 (1986)

Passive Solar in the United States: 1976-1986

J. Douglas Balcomb*
Los Alamos National Laboratory
Los Alamos, New Mexico 87545

Abstract

A decade of experience in passive solar development in the United States is reviewed. More than 200,000 residential and 15,000 institutional and commercial passive solar buildings have been constructed since 1976. The evolution of the program through its peak in 1980 to the present is described. Methods of performance prediction and evaluation are discussed including analysis methods, design tools, test modules, and monitored buildings. Results of the monitoring show

---

*On a two-year leave of absence until October 1987, as Distinguished Research Fellow, Solar Energy Research Institute, 1617 Cole Blvd., Golden, Colorado 80401.

excellent performance, generally in agreement with the analysis, for both residences and larger buildings. Passive practice is analyzed and problems are discussed. The current research program is described and potential savings are estimated.

INTRODUCTION

Since 1976 there has been a major effort to promote passive solar energy applications in the United States. Largely this has focused on passive solar heating of single family residences; however, work has also been done on multifamily and commercial buildings and on natural cooling and daylighting. Estimates suggest there are now more than 200,000 residential and 15,000 commercial passive solar buildings in the United States; thus it is an accepted and proven technology (Renewable Energy Institute, 1986).

Detailed computer simulation models have been used extensively to predict the performance of passive solar buildings. Design tools usable by architects have been developed by correlating the results of numerous computer simulations of different passive solar strategies in different climates. Design guidelines have evolved for balancing conservation strategies and passive solar strategies depending on climate and economics. Design competitions have been used effectively to promote the construction of many buildings throughout the country.

A major government program launched by the U.S. Department of Energy (DOE) to quantify the performance of passive buildings resulted in the detailed monitoring of more than 100 residential and 22 commercial structures. In general the performance has been excellent and the occupants have been very satisfied.

The most important conclusion from this decade of work is that we have learned how to design, construct, and operate buildings that use a fraction of the energy of conventional buildings, that provide a more comfortable and livable interior environment, and that cost little or no more to construct.

RECENT HISTORY OF PASSIVE SOLAR DEVELOPMENT

Although historical and prehistorical examples of the use of passive solar by Americans do exist, very few buildings were consciously designed to use passive solar energy prior to the 1970s. Some direct gain buildings were constructed in the Midwest in the 1930s and other isolated examples can also be found. A group of engineers at the Massachusetts Institute of Technology experimented with passive solar test rooms in 1946. Significantly, although they measured reasonable performance in the cloudy Boston climate, the group abandoned this line of research in favor of systems with solar collectors, pumps, and storage tanks, setting the stage for the future. Thus did active solar become the prime strategy promoted for the major solar development program triggered by the OPEC oil embargo.

The first evidence of strong interest in passive solar appeared in 1976 at a passive solar conference held in Albuquerque, New Mexico. Annual national conferences have been held since then with interest continuing to be strong through 1982 and declining somewhat in the last few years as public concern over all energy issues has slackened.

Support for both research and commercialization of passive solar by government agencies lagged behind support for active solar by about four years; however, this situation has now reversed. Passive receives the greatest emphasis, largely because of the good performance, low cost, ease of maintenance, and good acceptance of passive solar approaches by both building designers and the public.

Peak funding for passive solar occurred during 1979-81 at which time DOE's expenditure on passive solar averaged $29 million per year (Renewable Energy Institute, 1986). This average has now declined to about $6 million per year for all solar buildings research. During the peak period the emphasis was on commercialization activities such as information programs, design competitions, training programs, and surveys of consumer attitudes. Almost all these activities have been phased out so that the present program is almost entirely devoted to research.

A recent and significant development is the realization that passive strategies can be very effective in institutional and commercial buildings. Usually the major passive strategy employed is daylighting because these buildings are used mostly during the daytime. However, a natural synergy exists between daylighting and passive solar heating if the windows used for daylighting face south. Also cooling requirements can be reduced because much of the cooling load is caused by heat generated by artificial lights (Gordon et al., 1986).

PERFORMANCE EVALUATION

Passive Solar Performance

The net energy benefit of adding passive solar strategies varies with climate and system type, design, and size. When the system and building conservation parameters are optimized for the climate, the net benefit (defined as a reduction in backup heat compared to a perfectly insulated wall) is usually from 50 to 100 $\mathrm{kBtu/ft^2}$ (150 to 300 $\mathrm{kWh/m^2}$) of aperture per year. Added cost for residential construction is usually from \$5 to $\$15/\mathrm{ft}^2$ (\$50 to $\$150/\mathrm{m}^2$) of aperture, and backup heat cost is from \$0.02 to \$0.07/kWh. The added cost associated with the passive solar features is usually 4%-8% of the total cost of construction of a residence and the payback time is usually within 5-10 years.

Performance Analysis

Scientists and engineers frequently do performance estimation using mainframe computer programs for hour-by-hour simulation analysis. This is normally for research or systems analysis rather than for the design of a particular building.

Two main mathematical approaches have been used to describe the dynamic behavior of buildings. The most straightforward is the use of thermal networks in which the flow of heat from point to point in the building and the storage of heat in massive elements are characterized by a set of ordinary differential equations. The other standard approach is to use weighting functions in which the time response on one side of a wall is described as a convolution of the inputs on both sides. Harmonic analysis is a third technique that is used less often. Each method has its advantages, disadvantages, and strong advocates.

Design Tools

Most passive buildings are designed without any analysis by emulating other buildings, by experience with other similar projects, or by using simple rules of thumb. When an analysis is made, the most widely used design tools are simplified monthly methods based on correlating the results of the numerous computer simulations. The most common of these is the solar load ratio (SLR) method in which the correlation parameter is the ratio of solar gain to building load (Balcomb et al., 1982, and Balcomb et al., 1984). This analysis can be done by hand or with the aid of one of the numerous microcomputer programs based on the method.

An effective design tool, targeted specifically for builders, is a set of builder guidelines written for a specific locality. This package, which has been demonstrated in several places including New Mexico and North Carolina, contains three parts: 1) target levels for building loss coefficient, auxiliary heat, thermal comfort (expressed as a winter temperature swing), and auxiliary cooling; 2) guidelines that will help the designer meet these target levels; and 3) simple fill-in-the-blank worksheets for calculating the above values for comparison with the target levels. The approach is nonprescriptive; it allows for a wide variation in the design of the building from superinsulated at one extreme to explicitly passive solar at the other extreme.

A trend is now developing for simulation programs that take full advantage of the increased computing power of the current generation of microcomputers. These are normally used in the design of larger structures such as institutional and commercial buildings in which the energy issues are much more complex than for residential buildings. We can foresee that computer-assisted design (CAD) techniques, now commonly used for drafting, will be expanded to include energy analysis.

Test Modules

Test modules, as described by Moore (1982), have been built in three general sizes: small test boxes, usually about a 3-ft (1-m) cube; test rooms, usually about 40 ft^2 (4 m^2) in area; and unoccupied larger test buildings. Each has proved to be valuable for different types of tests and for teaching college students the principles of monitoring, data evaluation, and comparing theory and experiment.

These test modules have played an important role in passive research. Numerous modules have been built at several institutions to obtain data under carefully controlled conditions. The units serve one or more of the following purposes: making direct side-by-side comparison of competing strategies, obtaining data for the validation of computer programs, and testing components under realistic conditions.

Test modules are sometimes operated in a free-running mode, that is, without auxiliary heating or cooling. More commonly, they are operated with a thermostatically controlled inside environment. This allows a more direct comparison of the net energy benefit of the units and yields a more realistic operating profile.

Monitored Buildings

Results of a large-scale program conducted by DOE indicate good performance of actual occupied buildings monitored over one or more years using 20 or more sensors connected to hour-by-hour recording equipment. Subsequent computer analysis of the data from 70 homes in various climates shows (SERI, 1984):

- These passive solar homes use 70% less auxiliary heat than conventional homes, with the average solar contribution being 37% of the total heating load or 55% of the net heating load (total minus internal gains from people, lights, and appliances).
- Among the various systems employed (direct gain, Trombe walls, and sunspaces), there was no noticeable difference in performance. In fact, many houses combined two or more solar options to good advantage.
- Building heat loss coefficients per unit floor area of 4-6 Btu/°F day ft^2 (0.9-1.4 W/°C m^2) are routinely achieved, underlining the importance of good conservation practice. Auxiliary heating requirements as low as 1-2 Btu/°F day ft^2 (5-10 Wh/°C day m^2) are demonstrated in sunny climates and values of 1.5 times these levels are achieved routinely in all climates.

- Solar fractions of 50% or more are often achieved; however, in a few cases the solar performance is illusory because losses from the solar elements exceed their solar gains.
- Movable insulation systems intended to reduce heat losses at night have generally not worked well; in fact, it is questionable whether they saved any energy at all. This is certainly due, at least in part, to the fact that outside roll-down shutters are not used in the United States. Most of the products that were used were of recent design, most were designed to fit inside the window rather than outside, and many were not mechanically reliable. The occupants, unaccustomed to the daily operation of such systems, tended to resent the extra effort involved.
- Occupants are very satisfied with their houses.

Comparisons were made of the monitored results with performance estimates based on the actual weather and solar conditions and inside temperature. Deming and Duffy (1986) and Duffy and Odegard (1986) found that both the SLR and the unutilizability method estimates match the auxiliary heat used quite well on average (within 4% for SLR and 13% for unutilizability). However, for a given passive solar building, the predictions can vary significantly from measurements (the root-mean-square difference is about 30% for both methods). Much of the discrepancy for individual houses appears to be because of uncertainties in the measured heat loss coefficient and not necessarily in the passive solar prediction.

Analysis of the data from 21 monitored institutional and commercial buildings by Gordon et al. (1986) shows:

- Overall energy savings, compared to "base-case" buildings of the same size and function in the same location, are about 47%. Lighting energy is reduced 68%, heating energy is reduced 44% and cooling energy is reduced 68%. Only the small category of "other" energy (mostly energy to run equipment and fans) is increased.
- Daylighting was a major design strategy in all of the buildings. The occupants appreciated the quality of the inside environment, especially the light.
- The buildings were used more than had been planned. This partly explains why the savings in heating energy is not always quite as large as predicted.

- The construction cost of the buildings was nearly identical to that estimated for the base-case buildings. The added cost of the solar options was partially offset by reductions in the cost of equipment.
- Peak demand for electricity was substantially reduced compared to the base-case buildings.
- Problems with controls were experienced in some of the buildings. Most often this was because the thermostat was set back too far at night or the heating system was started up too late in the morning, resulting in an uncomfortably cool building on early winter mornings.
- The cost of designing the buildings was higher than for conventional buildings because of the extra effort of integrating the passive solar and other systems. This cost difference probably will lessen in time as daylighting and passive solar become more routine and as better design tools become available.
- The important lesson that Ternoey et al. (1985) stress is that the key to achieving good overall energy performance lies in the **integration** of daylighting, passive solar heating, and natural cooling into the overall design.

PASSIVE PRACTICE

In less than a decade "passive solar" has become part of the vocabulary of building designers, buyers, realtors, financers, and researchers. Coined in the early 1970s, the term was intended to emphasize an alternative to the then-popular active solar technique. Because it employs conventional building materials and because the basic concepts are easily understandable, passive solar has been readily accepted among designers and builders. The term passive solar is now used to include the strategies of passive solar heating, natural cooling, and daylighting.

By itself, passive solar does not make a good building, as many of the early examples demonstrate. Many other factors, such as sound architectural design and good siting, must also be correct. However, passive solar provides visible testimony that good energy design has been a priority. Some of the factors that have proved to be effective, considering both technical and marketing issues, are discussed below (Balcomb, 1984).

Residential Buildings

All-solar subdivisions. Generally only an early innovator is likely to buy a solar building located among nonsolar buildings. By contrast, clusters of passive solar buildings signal a trend and evince a degree of societal acceptance necessary to most people undertaking a large financial obligation. In buying a solar home amidst other solar homes, rather than feeling innovative, the buyer becomes part of the trend along with his neighbors.

Site planning and development. With a little forethought, good solar access can be planned into a development with no loss in density. Zoning restrictions can be adopted that guarantee continued solar access to every building.

Sunspaces. Sunspaces have become extremely popular in the United States, both for new construction and for retrofit of existing buildings. They provide a sunny living area and are often, but not always, used for growing plants. Properly designed, they require no backup heat, furnish as much passive solar heat to the house as the same glazed area of direct gain or Trombe wall, and do not overheat in summer.

Balanced conservation and passive solar. The economic tradeoff between more insulation and more solar gains leads to an easily derived, optimum design solution that is climate dependent. However, the curve is fairly flat so that near-optimum performance can be realized over a reasonably wide range of design choices. But in all cases good insulation practices and low infiltration are essential. If inadequate conservation measures are employed, the required solar area will be too large, thermal mass requirements for adequate heat storage will be too great, and control will be difficult.

Good thermal comfort. Thermal comfort requires stable interior temperatures, which means that the building should have small temperature swings under free-running conditions. Stable temperatures require adequate thermal mass for heat storage, a proper relationship between the location of solar gains and heat storage, and effective thermal distribution. Without these essentials, the building will not create the type of internal environment necessary to ensure the adoption of passive solar buildings on a large scale.

High quality of construction. By adhering to the principles outlined above, the designer already will have integrated good thermal quality into the building. It is only consistent to follow this up with good materials and high quality construction to ensure that the building will perform well over the long term.

Institutional and Commercial Buildings

Daylighting. Good daylighting design, which was well understood and practiced before the advent of the fluorescent lamp, is now coming back. The use of natural light in buildings is not only essential to good architecture but it makes good energy sense. By using windows, light shelves, clerestories, roof monitors, and atria, daylight can be brought into most rooms of most buildings. Natural light not only reduces the need for artificial light but also reduces cooling loads produced by the lights because natural light contains more light per unit of heat. Good daylighting design avoids direct penetration of sunlight into the building. Instead, sunlight is diffused from strategically placed louvers or baffles that are painted eggshell white to achieve colorless soft lighting. Glare is avoided by placing all such diffusing surfaces and diffusing glazing well above eye level. By orienting windows used for daylighting to the south, both heating and cooling loads are reduced. Artificial lighting systems and their controls must be well integrated with the daylighting or energy may not be saved.

Atria. The atrium has become a popular design element for architects, adding character and vitality to the building. Atria are very complex both thermally and optically and their effect on a building is not well understood. They can have either a positive or negative impact on the energy dynamics of a building depending on the design.

Balancing. Thermal balancing of the building must be done on a space-by-space basis and also on a time-of-day basis considering orientation, patterns of internal heat generation, and occupancy. Mismatches between the availability of natural energies and the energy needs of various spaces may require transporting heat from space to space with inevitable increases in complexity and cost.

Regionalism

There is now a growing trend toward regionalism in architecture. This fits in well with passive solar design because building types that evolved before this century were often based on accommodating the climate. This is particularly evident in the southeast United States where several traditional housing types effectively use sun protection and natural ventilation. Often it is the same designers who are concerned with historical preservation, use of traditional building styles and techniques (updated to use modern materials and methods), and passive solar design. We hope that the current total emphasis on stylistic issues will gradually shift toward a return to a functionalism that pervades the entire building design.

PROBLEMS

Passive solar development has not been without its problems, two of which are discussed below.

Overheating

Overheating by the sun can occur in winter or summer, but is usually because of different design errors. Winter overheating can occur if the south glazing is oversized or thermal storage mass is insufficient for the amount of direct gain. Good design practice is to limit the collecting area for solar gain to a value that would result in an average inside temperature no greater than 72°F (22°C) on a clear January day. Thermal storage should be sized to limit the inside temperature swing to no more than 9°F (5°C) on a clear winter day. In any case the area of direct gain should not be greater than about 13% of the floor area of the building or glare, ultraviolet fading of materials, and loss of privacy will result. If a larger solar glazing area is desired, then an indirect system such as a Trombe wall or sunspace should be used.

Summer overheating can usually be traced to excessive east, west, or horizontal glass in the design. This is a common problem in sunspaces. The remedy is to emphasize south-facing glass and avoid large glazing areas on any other orientation. If skylights in houses or overhead glazing in sunspaces are used, they should be covered in the summer. Proper natural ventilation of sunspaces is also essential to avoid high inside temperatures in the summer.

Perception

This is listed as a problem because understanding of passive solar by the public, the building industry, and design professionals is not nearly as good as it could be. The excellent performance results that have been obtained are not widely recognized nor is a need for saving energy seen as a priority. Most people are very conservative about their homes and are reluctant to make any changes in style or appearance.

There are two solutions to these problems of perception. The first is public education: publicizing effective and attractive passive solar buildings can alleviate many of the concerns. Exotic concepts, such as underground buildings or extremely modernistic designs, are likely to meet resistance and should be avoided. Certain building types, such as schools and libraries, provide excellent opportunities for passive solar and daylighting and should be used as demonstrations. Experimentation on new concepts should be confined to the laboratory; only tried and proven systems should be put into buildings that are to be used because errors are always publicized and are very harmful to the image of passive solar.

The second solution is to establish a good program of educating architects both within colleges of architecture and in short courses for practicing architects. Education of builders can best be done through builder guideline packages and seminars.

FUTURE RESEARCH DIRECTIONS

Currently, government funding for passive solar is primarily for research with emphasis on systems analysis and on new products and materials. The objective of the research is both to improve performance and to achieve greater penetration of passive solar techniques into the marketplace.

Systems analysis is aimed at improving our understanding of how passive systems work in buildings, determining the most effective directions for research, and developing design tools. Daylighting is receiving priority in institutional and commercial buildings. Natural cooling continues to be investigated although it has thus far been difficult to implement and quantify. New design tools are being developed. Methods of maximizing the information that can be derived from short-term monitoring are being investigated.

New products and materials research emphasizes work on improved glazings and other aperture materials with three objectives: reduced heat losses, improved transmittance, and greater controllability. Coating on glazings that have a low emittance in the infrared are now common, and efforts are being made to improve their performance. Coatings with optically switchable properties are being investigated using thermochromic, photochromic, or electrochromic phenomena. Aerogels and evacuated glazings are being investigated with the objective of reducing heat transmission coefficients to as low as 0.1 Btu/°F h ft^2 (0.6 W/K m^2) while maintaining at least 50% optical transmittance. Work is also being done on improving thermal storage capacity of building materials by impregnating them with a phase change material.

THE $64 BILLION QUESTION

Residential buildings in the United States consume approximately 15 quads* (4.4×10^{12} kWh) of energy annually, and commercial and institutional buildings consume 10 quads (2.9×10^{12} kWh). The sum of these represents 36% of U.S. energy consumption at an annual cost of $160 billion per year. Of these 25 quads, electricity represents 62% while natural gas and oil represent 36% and 10%, respectively. The major uses are space heating (9.7 quads), lighting (3.7 quads), cooling/air conditioning (3.7 quads), hot water (3 quads) and appliances and other uses (5.4 quads).

The potential for displacing these energy requirements by using conservation and passive solar strategies depends on several factors: the potential savings for each building, the fraction of new buildings that use these strategies coupled with the rate of new building construction, and the rate of retrofit of existing buildings. Using reasonable estimates for the maximum credible market capture for these strategies, one can predict an annual savings of perhaps 10 quads (2.9×10^{12} kWh) per year in year 2010, corresponding to an annual savings of at least $64 billion in current dollars. Note that this savings would accrue each year at no additional expenditure of capital. This enormous potential should easily justify a much greater emphasis being placed on these strategies; however, it probably will not be realized if current attitudes continue.

---

*1 quad = 10^{15}Btu

In addition to building owners, many would benefit from achieving the full potential of conservation and passive solar strategies. Our national security and prosperity would be enhanced because of reduced dependence on energy imports and the reduced need for new electric generating capacity, freeing vast capital resources to be invested in modernizing U.S. industry. Environmental quality would be enhanced as a result of the reduced level of extracting and burning conventional fuels that pollute both the air and water. The private building industry and their product suppliers would benefit from an increased level of construction, especially for retrofit of existing buildings. Building designers would benefit because of a greatly increased need for their services. Unemployment would be reduced in response to increased demand for local construction skills.

CONCLUSIONS

Passive solar development has been partially successful in the United States but current public complacency about energy issues in general has greatly slowed penetration into the market. This complacency is clearly associated with decreases in oil prices even though the cost of energy for building heating, cooling, and lighting is no lower than it was in 1977-79 when interest was increasing.

We have learned how to build much better buildings and to use passive systems to effectively harness environmental energies. The challenge now is to maintain the momentum. The best way I see to do this is to emphasize that passive solar leads to a higher quality interior environment. The energy issue has already received ample attention. Now we should stress the good thermal comfort possible with passive heating and cooling and the delightful character of natural light. Since a major purpose of the built environment is to provide shelter and comfort, we should let it be known that passive strategies can do this very well indeed--and can do it reliably and economically.

REFERENCES

Balcomb, J.D., 1984. Passive solar research and practice. *Energy and Buildings* 7:281-295.

Balcomb, J.D., R.W. Jones, R.D. McFarland, and W.O. Wray, 1982. Performance analysis of passively heated buildings: expanding the SLR method. *Passive Solar Journal* 1(2):67-90.

Balcomb, J.D., R.W. Jones, R.D. McFarland, and W.O. Wray, 1984. *Passive Solar Heating Analysis.* Atlanta, GA: ASHRAE.

Deming, G., and J.J. Duffy, 1986. Un-utilizability design tool predictions compared to auxiliary measurements of passive solar residences. *Proc. 11th National Passive Solar Conf.* (Boulder, CO, June 7-11, 1986). Boulder CO: ASES, pp. 88-93.

Duffy, J.J., and D. Odegard, 1986. Solar load ratio design tool predictions compared to level B monitoring data. *Passive Solar Journal* 3(1):77-97.

Gordon, H.T., P.R. Rittleman, J. Estoque, G.K. Hart, and M. Kantrowitz, 1986. Passive solar energy for non-residential buildings. *Advances in Solar Energy*, 3. New York: Plenum Press.

Moore, F., 1982. Passive solar test modules. *Passive Solar Journal* 1(2):91-108.

Renewable Energy Institute, 1986. *Annual Energy Technology Review, Progress Through 1984.* Washington, DC: Renewable Energy Institute (1001 Connecticut Ave., Suite 719, Washington DC 20036).

SERI, 1984. *Passive Solar Performance, Summary of 1982-83 Class B Results.* SERI/SP-271-2362. Golden, CO: Solar Energy Research Institute. (See also SERI/SP-281-1847, published June 1983, for 1981-82 results.)

Ternoey, S., L. Bickle, C. Robbins, R. Busch, and K. McCord, 1985. *The Design of Energy-Responsive Commercial Buildings.* New York: Wiley-Interscience.

Passive Solar Journal, 3(4), 349-386 (1986)

Daylighting in the Mt. Airy Public Library

Mari Adegran*
Brandt Andersson
Wayne Place*
Building Systems Analysis Group
Lawrence Berkeley Laboratory
Berkeley, California 94720

Abstract

Results are presented from a detailed case study that evaluates the visual environment of a daylit building, the Mt. Airy Public Library, in Mt. Airy, North Carolina. This passive solar building is designed to save energy through the use of daylighting from south-facing clerestories, in combination with more traditional

---

*Ms. Adegran is currently with Columbus Architects, 916 Kearny St., San Francisco, California 94133. Dr. Place is currently with the Architecture Department of the North Carolina State University, Raleigh, North Carolina 27605.

energy-conserving techniques. It is part of the U.S. Department of Energy's Non-Residential Experimental Passive Buildings Program and has been evaluated during the design and construction phases as well as monitored during more than a year of occupancy.

This case study focuses on the quality of the daylight and compares it to recommended practice and alternative lighting environments. We carefully measured and observed light distribution throughout the entire building, including luminance distribution, task luminance, contrast rendering, and veiling reflections. We also observed and interviewed occupants concerning their responses to daylighting, electric lighting, and lighting control opportunities. These data were used to characterize and evaluate the visual environment of the library. The difference in performance between peripheral areas with vertical view glazing and the center core with south-facing clerestories is of special interest, since it has a major impact on the visual environment.

INTRODUCTION

Daylighting is an important technique for energy-saving design in commercial buildings. Among passive solar strategies, daylighting often has the largest impact on energy consumption, since the energy used for artificial lighting usually represents between 30% and 50% of a traditional commercial building's total energy consumption. It also can have a substantial impact on heating and cooling in many climates.

The energy cost, however, is a relatively small piece of the total cost in a commercial building compared to salaries and cost for employees, which represent the major part of the overall life-cycle cost. The most important economic argument for daylight design is occupant satisfaction and comfort, the provision of a productive and comfortable environment. Human needs and preferences for daylight are as important as the attempt to achieve energy-efficiency, and evaluation of the qualitative aspects of daylight is as important as the analysis of energy use.

The main goal of this study is to characterize the visual environment in a successfully daylit passive solar building. This is done by evaluating: 1) the patterns of occupant behavior in relation to different lighting situations, 2) visual comfort as a result of the quality of the light in various configurations, and 3) the range of visibility. We used both subjective and analytic methods. This study is complementary to other daylighting, thermal, and occupant studies in which the Mt. Airy Library has been a subject.

Past evaluations of daylight design by the architectural community have emphasized architectural effects, and those of the energy research community have focused on energy-conserving aspects. In buildings where both these types of evaluation have been made, the effect of daylighting on visibility, visual comfort, and occupant response must be included for a complete and comprehensive analysis of the buildings' performance (Ne'eman, 1984; Ne'eman et al., 1984). This study presents a method for achieving such an evaluation. The buildings program described below allowed for such a study.

BACKGROUND

As part of the Non-Residential Experimental Passive Buildings Program funded by the U.S. Department of Energy (DOE), 20 commercial buildings utilizing various energy saving techniques have been built throughout the United States (DOE, 1983). They all incorporate conservation features and passive heating, cooling, and/or lighting techniques. The design and construction phases are completed, and the program has entered the performance evaluation phase. Data have been collected for each project for a one-year period after occupancy. This is done through meter readings and submetering, or by automatic monitoring with microcomputer data acquisition systems.

In 80% of the buildings in the program, roof apertures, typically clerestories with vertical glazing, are a major passive feature contributing to both heating and lighting of the buildings (Gordon and Kurkowski, 1983). Most of the buildings also depend on manual control of the lighting system. In these ways, Mt. Airy Library is representative of many of the projects in this program, and several studies on it have already been completed (Gordon and Fisher, 1982;

Andersson et al., 1983; DOE, 1983; Gordon and Kurkowski, 1983; Andersson et al., 1984; Adegran et al., 1984; and Andersson et al., 1985). The addition of this case study will complement this extensive performance evaluation.

Mt. Airy Public Library in North Carolina is one of two buildings in the Non-Residential Experimental Passive Buildings Program that Lawrence Berkeley Laboratory (LBL) has studied extensively. The focus of those studies is on the energy (lighting, heating, cooling) effects of the south-facing clerestories, which are representative of so many other buildings in the program. This study provides a unique opportunity to assess the practical and technical advantages and disadvantages of the daylighting technique used.

BUILDING DESCRIPTION

Climate and Site

The 1300 m^2 (14,000 ft^2) public library is located in Mt. Airy, North Carolina, a rural community at latitude 36.5° N. The nearest city is Greensboro, 25 miles southeast of Mt. Airy. It is a climate with heating degree-days of 2200°C day (4000°F day), base 18°C (65°F), and cooling degree-days of 610°C day (1100°F day), base 24°C (75°F). The winters are relatively mild, and summers are warm and humid.

Architecture

During the design phase, the architects, Edward Mazria Associates and J. N. Pease Associates, worked to integrate the architecture with the daylighting design, which after several energy studies became the main conservation strategy of this passive solar building. Other passive elements include direct gain heating and natural ventilation. Five air-to-air heat pumps with programmable controllers provide auxiliary heating and cooling.

The building is a heavy mass structure with all exterior walls of solid grouted masonry insulated outside and faced with local granite (Figures 1 and 2). The concrete slab is finished with clay tiles. This structure provides for thermal energy storage, since the diffused solar radiation from clerestories and view glazing can be absorbed throughout the building. No other mass storage technique is utilized.

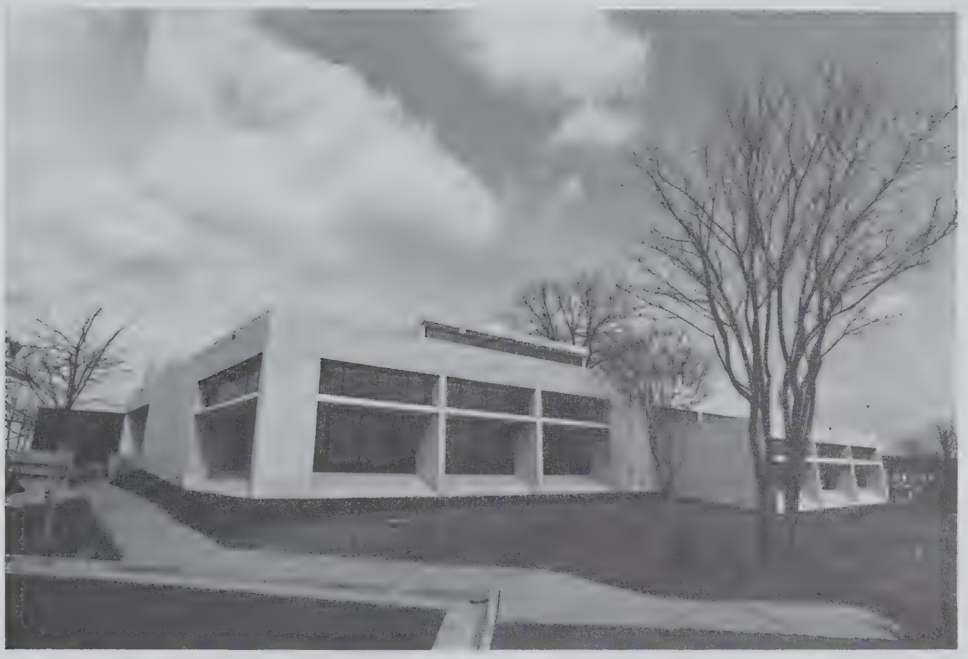


Figure 1. Mt. Airy Library, south elevation

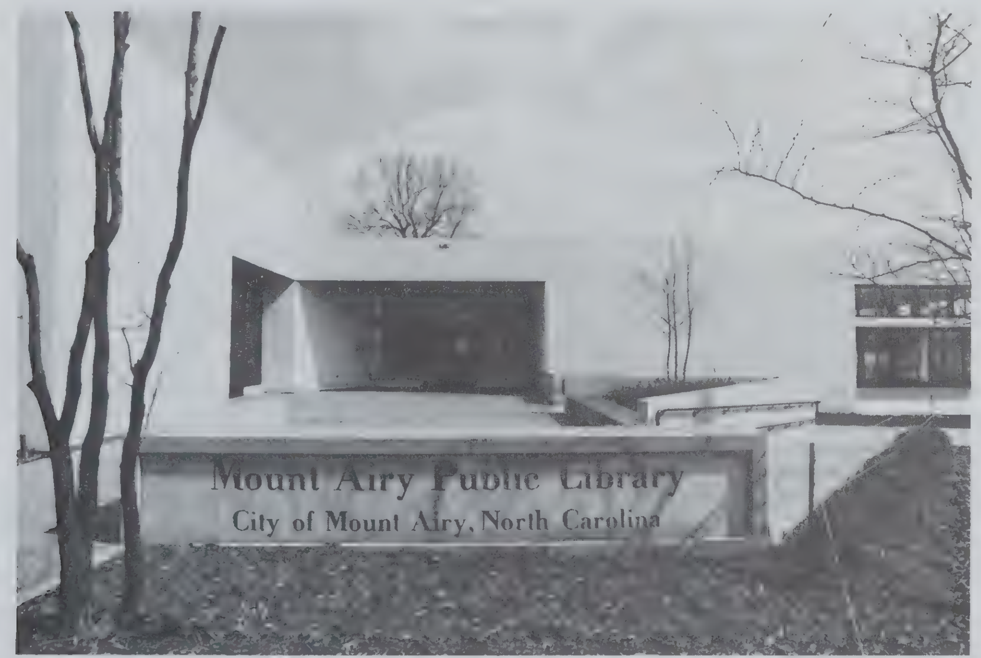


Figure 2. Mt. Airy Library, west elevation

Daylighting Strategy

The lighting system is a daylighting scheme with manually controlled auxiliary task and ambient artificial backup systems. Daylight is provided through a variety of methods. The main technique is the clerestories repeated along the north-south axis of the center area (Figure 3). The total glazing comprises 340 m^2 (3640 ft^2), which is 11% of the total envelope area and 26% of the floor area. Of the total glazed area, two-thirds [225 m^2 (2425 ft^2)] is facing south and the south-facing clerestories represent one-quarter [85 m^2 (910 ft^2)]. [For further discussion of the optimum of roof aperture area see Place et al. (1983).]

Another major daylighting feature is the set of solar control surfaces around the view glazing: the lightshelves and fins that shade light from some areas and reflect it into others. Since the configuration permits only limited amounts of direct gain for high sun angles, summer overheating is eliminated (Figure 4). In Figure 5 the sun pattern is shaded to show parts of the floor struck by the sun at winter solstice when the shading allows for maximum direct gain. The sloped ceiling in the stacks and multipurpose room are intended to perform as secondary light sources, reflecting light down to the areas below. Areas requiring higher levels of task illumination are strategically located under the clerestories or lightshelves along the south-facing fenestration in the perimeter for maximum use of natural daylighting (Figure 3).

General area illumination is accomplished by bouncing light from reflective surfaces, indirectly illuminating the spaces with light of uniform quality. Lack of partitions in the open plan improves daylight distribution and enables a deeper penetration. The color scheme also contributes significantly to the bright impression of the interior. Floors are covered with a warm, light beige, clay tile, and only the multipurpose room and parts of the magazine area and children's area are carpeted. The carpet is also a light beige. Most of the furniture is of blond natural wood, and table tops are usually light beige, matte Formica. The lending desk has a grass-green top, and the suspended light tubes add a spark of bright yellow to the otherwise mute and natural color scheme. All walls and ceilings are painted white except for a few areas with suspended ceiling finished

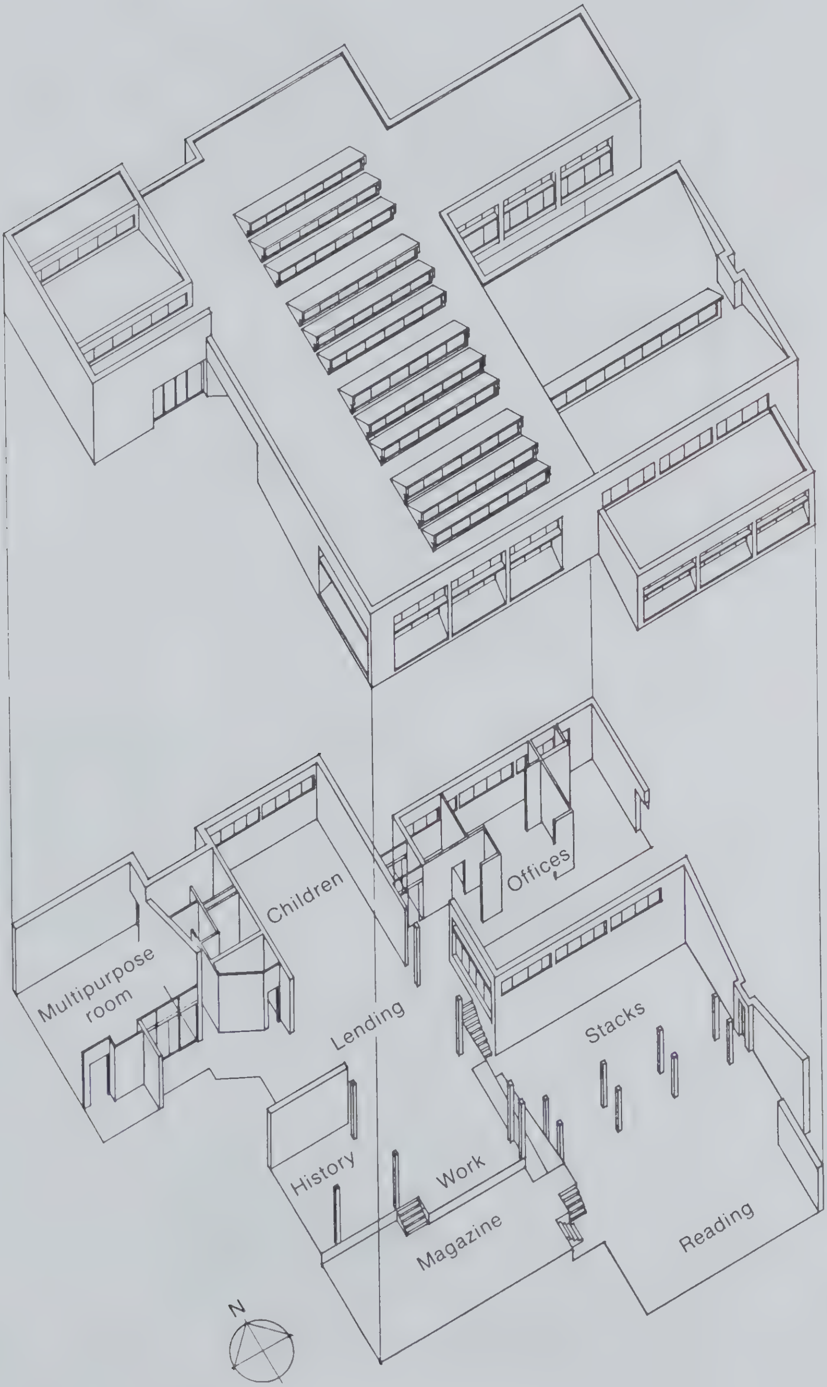


Figure 3. Axonometric showing all fenestration

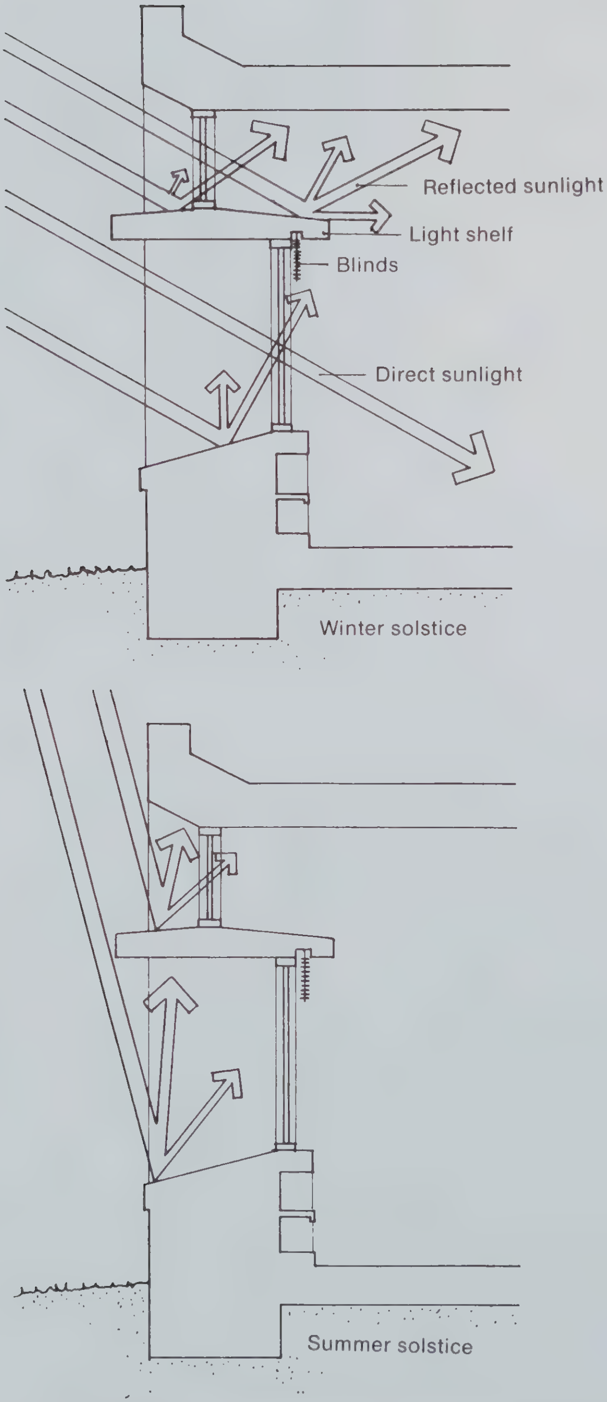


Figure 4. Section through south-facing wall glazing

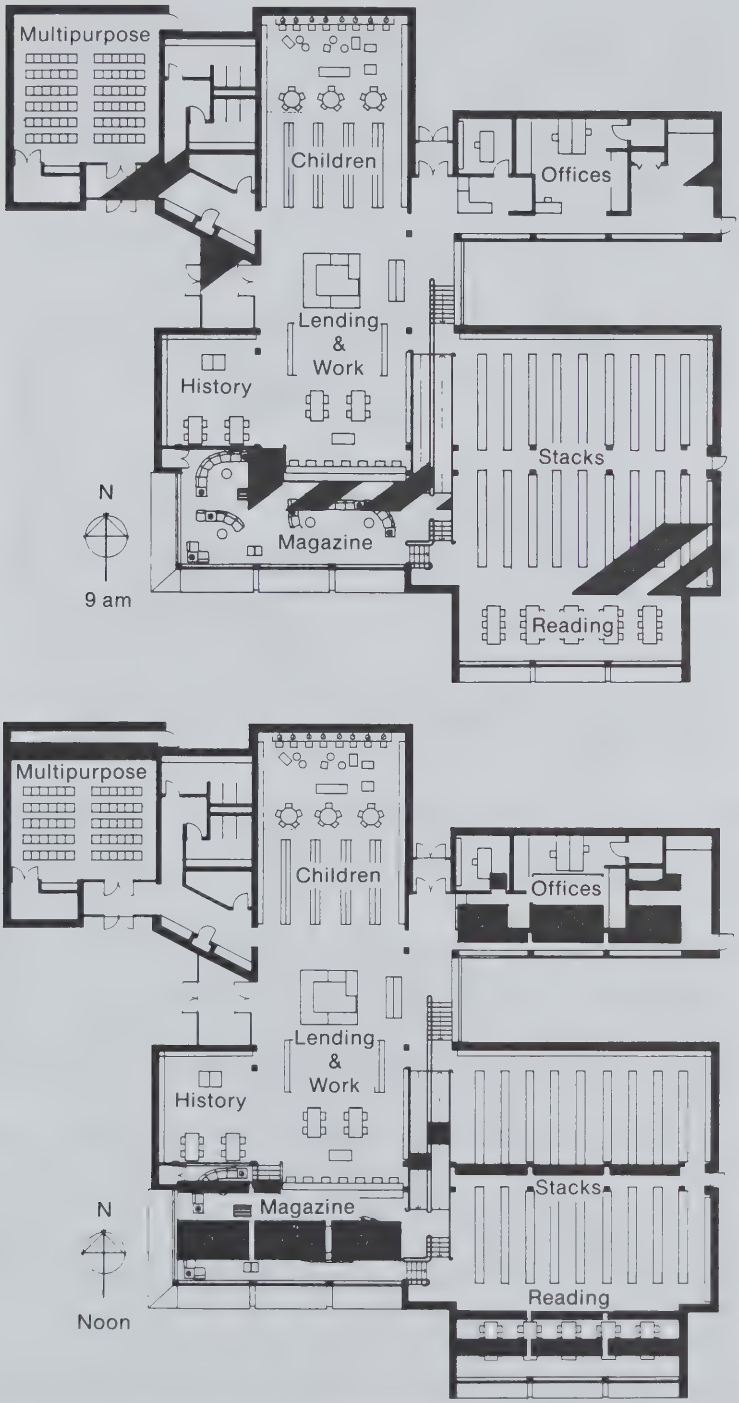


Figure 5. Sun patterns at the winter solstice: 9 a.m. - noon - 4 p.m.

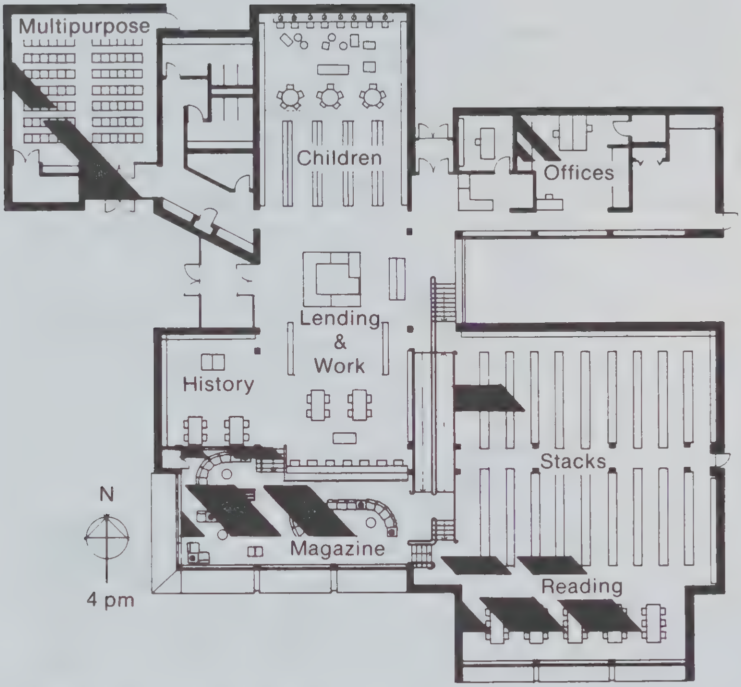


Figure 5. Sun patterns at the winter solstice: 9 a.m. - noon - 4 p.m. (concluded)

with parallel slats of blond natural wood. The concrete posts and clerestories are unfinished and add to the general impression of the interior as natural and simple.

All windows are standard double-pane clear glass, providing good daylight transmission and thermal resistance. Some of the windows are operable for natural ventilation. Venetian blinds provide glare and heat control for the visitors in the magazine and reading areas.

The architect and solar designer predicted the lighting energy requirements of the building, based on model studies for various solar conditions and their expectation of lighting control in response to daylighting. In fact, based on a year of monitoring, the lighting electricity use was 57% lower than predictions, 80% lower from June to September.

Many of the ambient electric lights are controlled by the librarians from the lending desk, to provide a more controlled switching capability, and the control is based on their individual judgments. Task lights are located not only at the lending desk, but also over the working counter in the center area, at the tables in the magazine area, in the children's area at the reading counter, and in the reading area next to the stacks; thus, visitors can also control their lighting environment individually.

Electric lights are placed in the clerestories in a concealed space (Figure 6), using the diffusing baffles to provide a less concentrated beam with an indirect light distribution similar to the daylight. White reflective surfaces and baffles work as in Figure 6, which illustrates the daylight distribution.

METHODOLOGY

Most daylight research is performed in laboratories where hypotheses are drawn and theories developed. Sometimes the research is done in conjunction with scale models for experimental data collection, but rarely are these results validated with field studies of existing buildings. This case study reports the results of extensive studies accomplished on this specific building. It offers an opportunity for detailed daylighting analyses in an actual environment.

The methodology, planned for and developed throughout the study, can be applied to all other daylit buildings. The study is based on information collected at the site by direct observation and on measurements during week-long winter and summer visits. Varying weather conditions occurred during each observation period, which allowed for studies under clear and overcast sky as desired. The occupants and the building were studied during occupied hours: 8:30 a.m. to 8:00 p.m. weekdays, and 10:00 a.m. to 1:00 p.m. Saturdays. (The library is also open Sundays from 2:00 p.m. to 5:00 p.m.) Studies of the electric light distribution and contrast rendition were completed at late night hours when no one was in the building.

Energy and occupancy data collected over 18 months as part of the standard performance monitoring provide a complementary data base. It includes information about energy consumption for heating, cooling, and lighting, changes in occupancy, set points for the thermostats, and staff and visitor responses to questionnaires concerning thermal and visual comfort, manual controls, and their attitudes about the building.

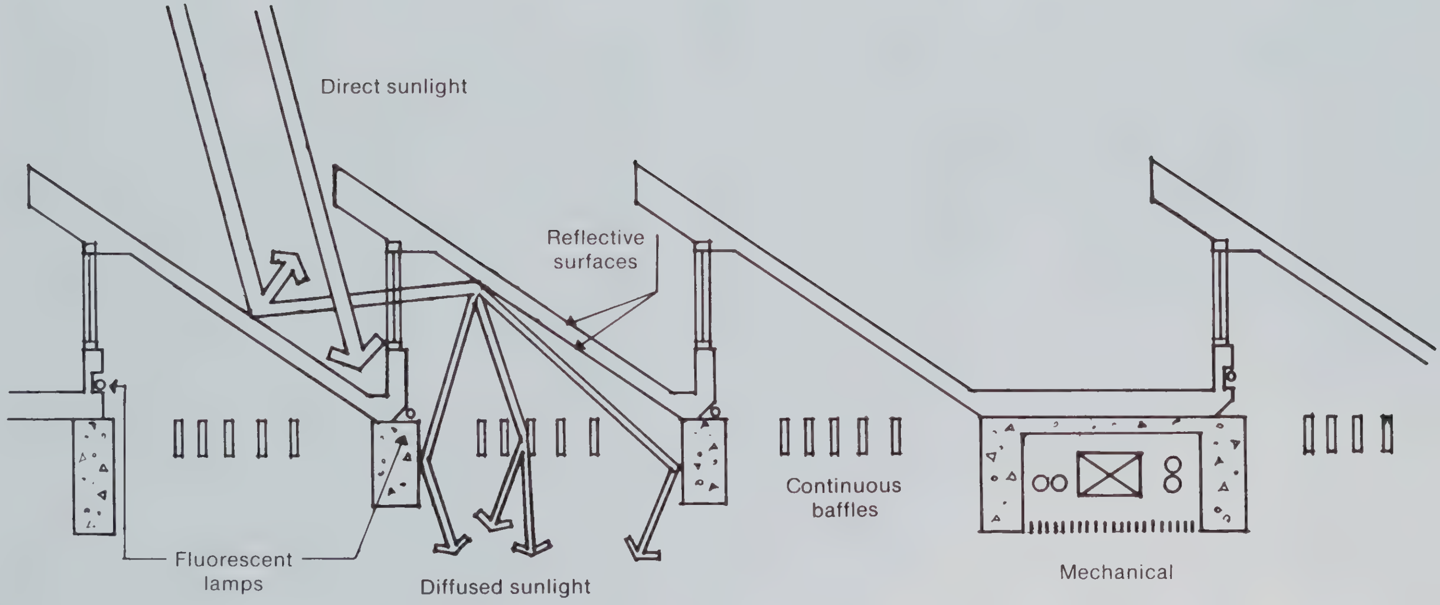


Figure 6. Detail: section through south-facing clerestory

Using the information described above, we divided this study into three parts: an investigation of occupant effect on daylighting performance and occupant response to the lighting environment, an evaluation of visual comfort, and an evaluation of visibility.

The physical environment is described, part of which is directly quantifiable, another part of which is qualitative.

Occupant Interaction

To better understand the lighting environment, it is important to study occupant behavior in response to various lighting situations. In this part of the study, we describe the occupants' behavior in different lighting situations to achieve the best visibility: where they most frequently sit and read, how they position themselves and their reading materials, when and how they change the manually operated shading and electric lighting controls, and how they use the space in general.

To determine whether an occupant's response depended on a previous disposition rather than a direct reaction to the environment, we developed a set of questions to determine their attitudes toward lighting control and shading operation, visibility, and visual comfort. The questions are organized in two groups, one for the staff and one for visitors. Respondents were encouraged to comment on the lighting characteristics at the time of the interview in their own words. See the appendix for the lists of questions.

Through the interviews and personal observations, we identified the occupancy schedule and pattern. Since we were interested in observing behavior under various lighting conditions, illumination levels were recorded at each occasion.

Visual Comfort

When excessively high luminances and/or high luminance variation exist within the field of view, visual discomfort may occur. Therefore the evaluation of visual comfort is based on the study of luminance levels and distribution, where it may be excessive, and adaptation to the environment. The brightness range of major surfaces in each space was determined from seated eye level in terms of luminance ratios.

Just as contrast is important for visibility, it is also important to visual comfort when seen in a larger perspective. When luminances and their relationships in the field of view cause visual discomfort but do not necessarily interfere with visual ability, it is called discomfort glare. If the eye moves from the task to the surrounding environment, it might encounter surfaces with high contrast, such as a bright window and a dark wall; that is an example of a situation that causes discomfort glare. According to Illuminating Engineering Society (I.E.S.) luminance ratio recommendations for office environments (I.E.S., 1981), no surface in the immediate surroundings of the task (such as the table top) should be less than one-third of the luminance of the task itself. For major surfaces anywhere in the field of view, the recommended maximum surface-to-task luminance ratio is 10:1, and the minimum is 1:10. The luminance ratios in the library are judged against these recommendations.

Scene contrast ratio is the ratio of the brightest to the dimmest surface in a space (maximum luminance/minimum luminance); it is the net effect of the individual values for all luminous areas in the field of view and is here used as a measure of the visual comfort. The lower the ratio, the more balanced and comfortable is the luminance distribution.

The bases of this evaluation of discomfort glare and visual comfort are the identification of representative observer locations, measurement of the light distribution, calculation of luminance ratios, description of surface configuration, and luminaire location.

The most important factor is observer location. The visual comfort study started with a careful observation of the occupancy pattern to find the location and kind of visual activity that is most significant in each space. From the representative observer location, we measured the different luminances in the visual field. A LiteMate spotmeter, with a one-degree reading angle, was used to measure the luminance. We measured luminances of all large surfaces in the field of view and all surfaces surrounding the task then calculated the luminance ratios between the areas. The visual task brightness (the luminance seen by the viewer) was recorded at each occasion and matched with pictures taken of text samples used for the visibility study. In some areas, we studied the luminance at the surfaces and at the task under two different types of lighting: daylight only, and electric light only.

The characteristics of visual comfort are also discussed from our personal and subjective point of view in addition to the interviews with occupants. It is also documented in black and white photographs that show the general lighting atmosphere.

Visibility

There are four important points that must be taken into consideration for a visibility study: the details to be seen, the condition of the observer's visual system, contrast rendition of the task depending on veiling reflections and illuminance level, and the luminance of the task and the relation to surrounding luminances.

Because this is a public library with occupants of all ages, there are varying kinds of activities in different parts of the building and therefore different lighting requirements. Samples of text and paper represent possible tasks. Because of the scope of the project, only the most significant areas, the areas with the highest use, are selected for detailed evaluation of visibility. The entire building is observed, but the areas chosen for more extensive studies reported here are lending desk and working area, magazine area, and stacks.

A longer version of this study (Adegran, Andersson, and Place, 1985) also presents information on the multipurpose room; children's, history, and reading areas; and offices.

The amount of light is important in determining the visual ability of the occupant, though it is not independent of other light phenomena. In addition to measurements of daylight distribution on the workplane, the visibility is evaluated in terms of ability to render contrast, since that ability affects visual acuity. As the contrast is raised, the probability of seeing an object increases.

For the study of contrast rendition at the task stations, we took black and white photographs of reference tasks at desk tops at a 25° viewing angle (Figure 7) recommended by I.E.S. (I.E.S., 1981). All pictures are taken with the same f-stop so that the contrast can be directly comparable even if the illuminance differs from photo to photo. They are then visually compared to pictures taken in a reference lighting environment, the sky simulator facility at the University of California, Berkeley. The sky simulator provides a

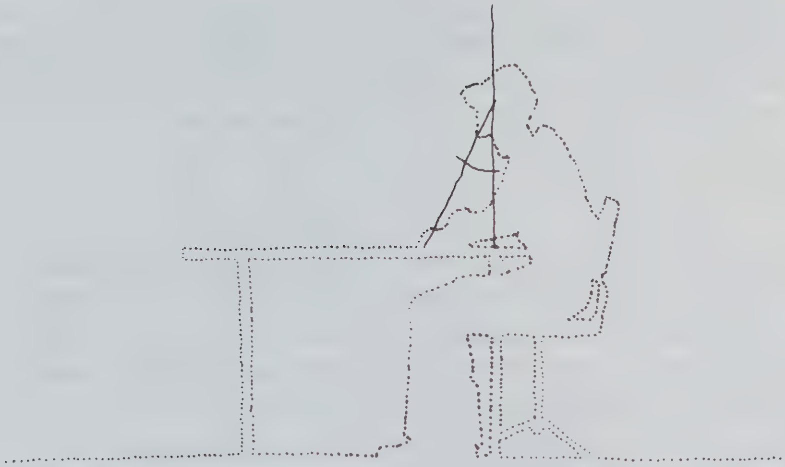


Figure 7. 25° task viewing angle

uniform light in an artificially lit hemisphere. The controlled lighting environment in the hemisphere has an illuminance on the task of 4700 lux (440 footcandles).

The procedure involves photographing a set of text samples and geometric objects under various lighting situations. The samples used represent different qualities of paper, from matte to glossy, with various type faces and a sample of pencil handwriting (Figure 8). A small cylinder, placed on the same board as the text samples, was found to satisfactorily show modeling, shadows, and the directionality of the light. In addition to daylit occasions, the electric lights were turned on after dark for one set of pictures at each location. With these photographs, the ability of daylight to render contrast can be compared to electric light. Since the sky condition and time of day changed at each occasion, we recorded the illuminance and can compare it to sets of illumination readings discussed below.

We used the same kind of film throughout the experiment, and all pictures are processed simultaneously with no change in development or print technique. A direct visual comparison of the general character of the contrast is possible even though it is not directly measurable. Because of the difficulty of discerning subtle details in reproductions of such photographs, we did not include them in this report, but discuss them with reference to the three samples in Figure 8.

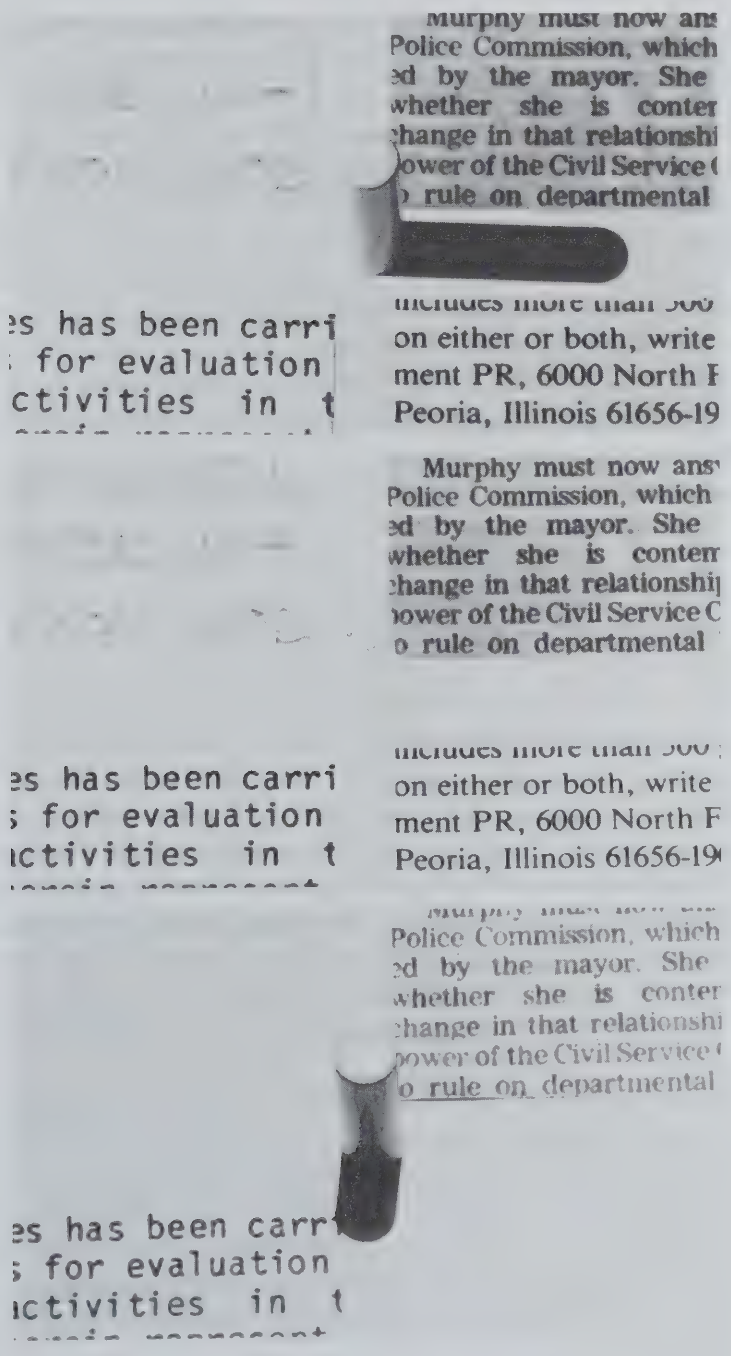


Figure 8. Reference task samples: various papers
(a) predominant light from the side of the observer
(b) uniform light from all directions (isotropic)
(c) predominant light from the front of the observer

Because quality and quantity of light are not independent considerations when providing a good visual environment, we also take into account the amount of light in this visibility evaluation. We took illuminance measurements from south to north at desk height, 76 cm (30 in.) above the floor, in the center of each space. The data points are typically 76 cm (30 in.) apart, but they are spaced closer in front of windows where illuminance variation is greatest. For night measurements with the electric lighting on, the readings were taken at exactly the same points. We took simultaneous exterior solar radiation readings from pyranometer measurements on top of the roof during the winter event. Unfortunately, the sensors were removed before the summer visit because the term for data collection had ended, but we recorded manual readings of the exterior illuminance immediately before and after every interior illuminance reading. We carefully noted the sky condition on each occasion.

RESULTS AND OBSERVATIONS

General

Occupant Response

The building is very popular among most of the staff as well as the visitors interviewed. "Very nice," "like it a lot," and "love it" were the most common answers when respondents were asked what they thought about their new library. Some expressed uncertainty about its modern appearance. A few respondents said that they had had to "get used to it" before they started to appreciate it. In general, the building has been very well received, and most people feel positively toward it.

The open plan invites a flexibility of use for which the lighting configuration is well suited. People move easily to an area with light and atmosphere to match their preference. Task lights are, for the most part, operated without any hesitation by the visitors. The ambient electric light and the blinds are rarely touched by either visitors or staff, although the intent of the designer was to have them operated by everyone to improve the light. Since the building has gotten so much attention and publicity, most occupants interviewed are aware of the energy saving intent of the design. How the energy saving design relates to the lighting is not clear to the visitors, but the staff is well educated by the City Engineer, who works next door and visits regularly, and the librarians make a conscious effort to keep the lights off when not needed.

Observations and interviews indicate that the lights are not kept off at the cost of visibility. Among the staff there is a shared responsibility to turn the lights on as well as off, though the main librarian in general is the supervisor. There is an obvious hierarchy between staff and visitors in operating ambient electric lights and the blinds as mentioned above. Most visitors feel a little uncomfortable about turning the overhead lights on or changing the position of the blinds. They say it is up to the librarians' judgment, and that it is "too much a part of the building" for them to initiate a change themselves.

When leaving, a majority of the visitors were observed to turn off the task lights they had been using. The librarians' comment was that the visitors are very bad at turning the lights off. Perhaps the different points of observation result in the contradictory information. Perhaps the librarians notice lights that are left on because then they must turn them off. They have no reason to notice a light that has already been turned off. Sometimes we may have assumed that the visitors turned out the task lights when it might have been the librarians. We believe, though, that visitors turned lights off more often than librarians since they clearly showed a responsible attitude about turning lights off, judging from observations and interview results.

Visual Comfort

One cause of an uncomfortable visual environment is excessively high luminances. Equally disturbing is a situation in which major surfaces have very different luminances. This is based on the principle that areas of high contrast in the field of view cause fatigue, since the eye has to adapt rapidly across a large range when the view shifts between surfaces with high brightness differences. Such continuous adaptation also affects visual acuity.

In simple terms there are two primary sources of visual discomfort: areas with excessively high luminances, and surfaces of high contrast in the field of view.

In the areas studied, luminance ratios exceed the I.E.S. recommendations in a few places but excessive luminance differences, sky glare, and visual discomfort are brought within acceptable limits through sensitive and aware design in most parts of the library. Since most of the room surfaces have reflective (40%-70% reflectivity) matte finishes, they serve as effective secondary light sources and materially reduce shadows by reflecting a significant amount of diffused light. That helps to prevent excessive luminance ratios and specular reflections that cause glare. Even on the brightest days, the lighting in most parts of the library is considered comfortable by staff, visitors, and ourselves. In addition, primary daylighting apertures are generally not visible from working and reading areas. Few areas with discomfort glare are identified, and the effects of beam sunlight entering the space (e.g., glare, radiant overheating) were not considered uncomfortable by any of the occupants interviewed.

Visibility

Because many variables interact within a lighting environment, it is difficult to establish definite values that define the effectiveness of a system in terms of visibility. Illumination is just one factor, and it has to be studied in relation to other phenomena such as contrast rendition, veiling reflectance, and luminance ratios. Since excessively high or low luminance causes fatigue in the eye muscles and loss of visual acuity because of the required change in the adaptation level, analysis of visual comfort aspects is relevant and necessary to a full understanding of visibility. Where no close visual work is to be done, the environment luminances are less important.

Referring to Figure 8, it can be seen that directional light, when provided from the side of the observer (a), creates the best light of the three situations shown. Uniform (isotropic) light distribution (b) is nearly as good. It is when a strong light source is located in front of the observer (c) that visibility suffers. The pictures taken of the text samples in electric light and in daylight show no extreme differences in visibility between the two systems. The daylight demonstrates its uniformity, and only slight differences in visibility were registered among the various locations. In general, the photographs were very similar to Figure 8b. In those areas where substantial sidelight was available, such as the magazine and reading areas, the contribution of light from roof apertures overhead is still substantial, so the overall balance is reasonable. In the offices, direct sunlight through the south hallway is balanced by light from north windows in the offices themselves.

The diffuse quality of the light demonstrated through the text sample photographs is not surprising. Great care was taken in most spaces to provide daylight coming from multiple directions. The provision of balanced, distributed daylight is an important contributor to visibility throughout the building.

Electric light is more directional and causes a lack of contrast and disability glare in some cases, though it is seldom perceived as a significant problem in the building. There is a difference between the pictures taken near task lights and those taken under just the overhead electric lights. This difference supports the belief that light sources of large area and low brightness perform better than small sources of high brightness, especially for glossy paper. Some configurations resulted in illumination closer to Figure 8c than 8a, depending on the relative location of the observer and task lights.

When people were asked to describe the light at the time of the interview, adjectives such as "restful," "pleasant," "fine," and "sufficient" were used. The impression library users have of the daylight is that the visibility is satisfactory in most parts of the building during most occupied hours, in winter as well as summer. Some comments on the low light levels in the stack area when only daylighting was available indicate a possible problem with the daylighting configuration there. One of the librarians with a south-facing desk close to the view glazing in the offices has problems with direct beam sunlight hitting her desk. It rarely affects her visibility, she said, but it is slightly uncomfortable, and is therefore classified as discomfort glare rather than disability glare.

In order to draw direct comparisons of the levels of illumination found in the different areas, the range of illumination at the workplane across different spaces is presented in Figure 9. We took measurements 76 cm (30 in.) apart throughout the center of each space. The variation represents the differences between different locations within each space. The spaces in which ambient electric

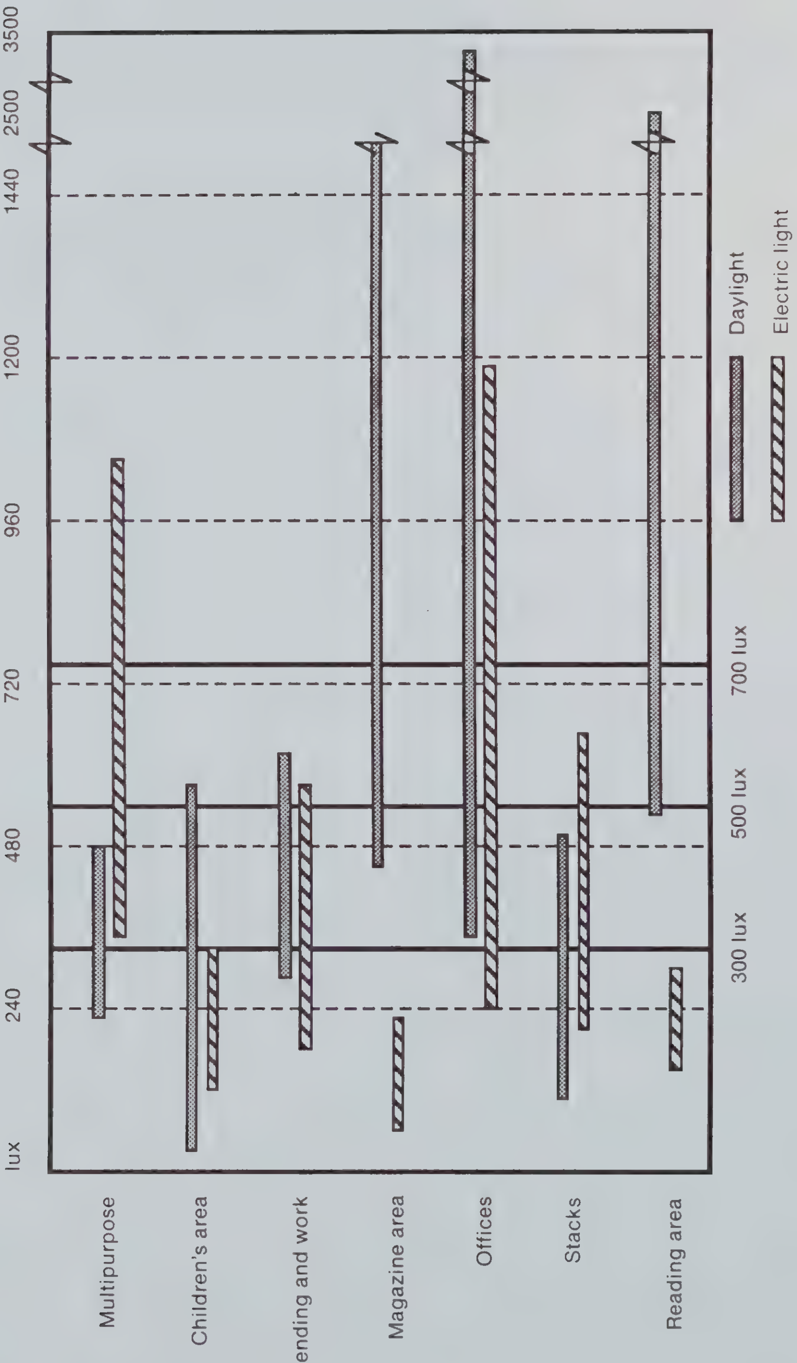


Figure 9. Comparison of illumination levels

lighting levels are very low (the children's, magazine, and reading areas) have supplementary task lighting available.

The average levels of illumination in the spaces are usually adequate by I.E.S. recommendations [330-760 lux (30-70 footcandles)]. The minimum levels were lower than the recommended levels in several daylit situations. There is evidence that the staff and visitors of the library are often satisfied with illumination levels below what is recommended. This may be the result of the mobility of library visitors, who are free to move to a better lit area, or to the fact that the tasks being performed often are not the most demanding which might be expected in a particular area. On the other hand, the recommendations may be unnecessarily high. Satisfaction with low light levels is thought to be one explanation why the manual lighting control system helps to save energy. The effect of various lighting control systems at Mt. Airy Library is investigated in detail elsewhere (Andersson et al., 1984).

Lending and Work Area

Occupant Response

The librarians spend a substantial part of their time at the lending desk and card catalogue, with tasks that require high visual clarity. There are often two persons here, and the desk is seldom unattended. This is the major work station, and the overhead suspended fluorescents are often on directly over the desk. It is here that the first lights get turned on at dusk. Most of the lights in this space and some in the children's area are controlled with light switches placed at a panel under the lending desk top.

The other set of task lights suspended over the south-facing work counter are operated with a switch at the column next to the counter. Occupants seldom turn these lights on themselves, and because of the location of the switch, it seems as if the librarians also forget to turn on the lights; therefore, the light levels can get very low in the evening even if visitors are sitting here working.

Visual Comfort

Since this is the part of the building that has the clerestories repeated along the south-north axis of the entire area, the light is evenly distributed throughout the space and is of a very uniform quality (Figure 10). The open plan and lack of partitions together with the lighting configuration and light colored surfaces create a space with many surfaces of varying brightness in the field of view, and few significant areas with very low brightness. The result is a mitigation of glare discomfort. There are a few sun spots entering the space in wintertime at lower sun angles because of gaps between the sets of baffles. They are not large enough to cause any glare; rather, they add to the quality of the lighting by making it more sparkling and alive.

The up-facing fluorescents in the adjacent stack area are a major cause of strong discomfort glare. Because the stack area is on a lower level, the unshielded lights are in the field of vision when viewed from the lending desk area (Figure 11). Glare from these up-facing lights is experienced from almost any location in the lending and work area, even at seated eye-level from tables in the work area.

Visibility

The daylighting levels generally provide adequate illumination for good visibility at all task locations in this space. The open plan, toplighting, and reflective surfaces all act to improve the contrast rendition with the evenly distributed light. Very little difference can be seen between the reference photographs of the task samples in comparison with the pictures taken in this area. No disability glare was detected for either electric lighting or daylighting.

The task luminance ratio at the lending desk is relatively high, since the work surface is fairly dark. The ratio of task luminance to its immediate surround is 10:1 rather than the recommended 3:1, so a lighter-colored working surface top would have improved the visual comfort, but the visibility is still satisfactory.

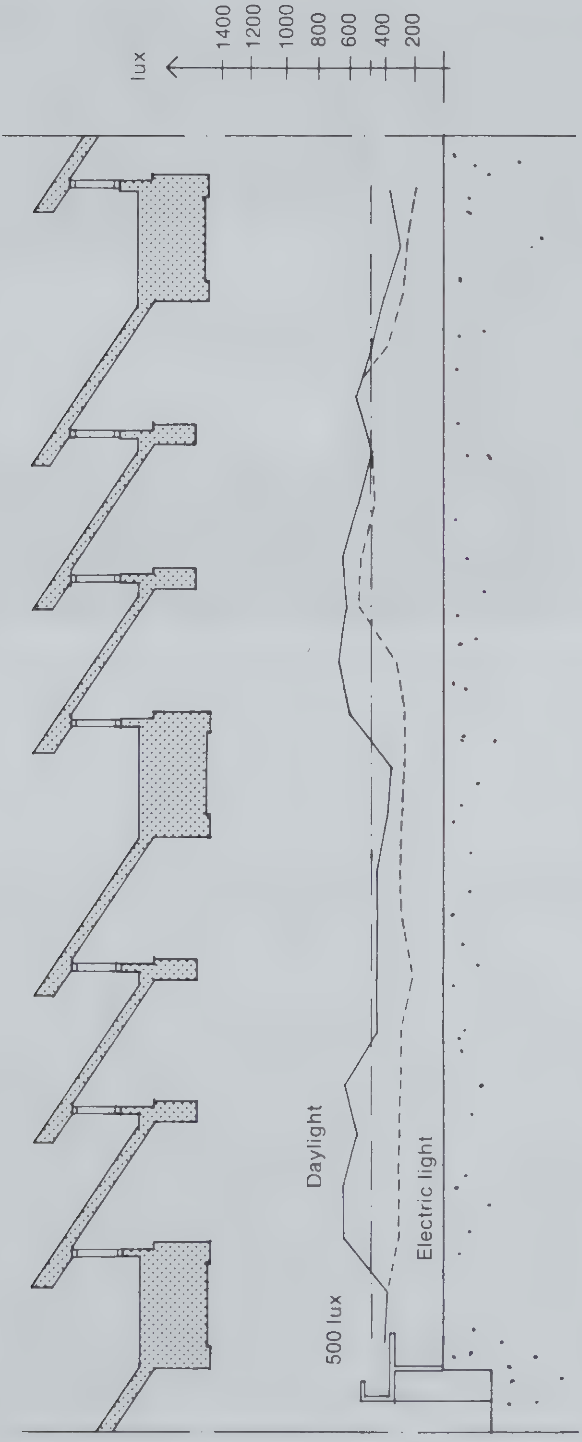


Figure 10. Lending and work area, daylight distribution, summer

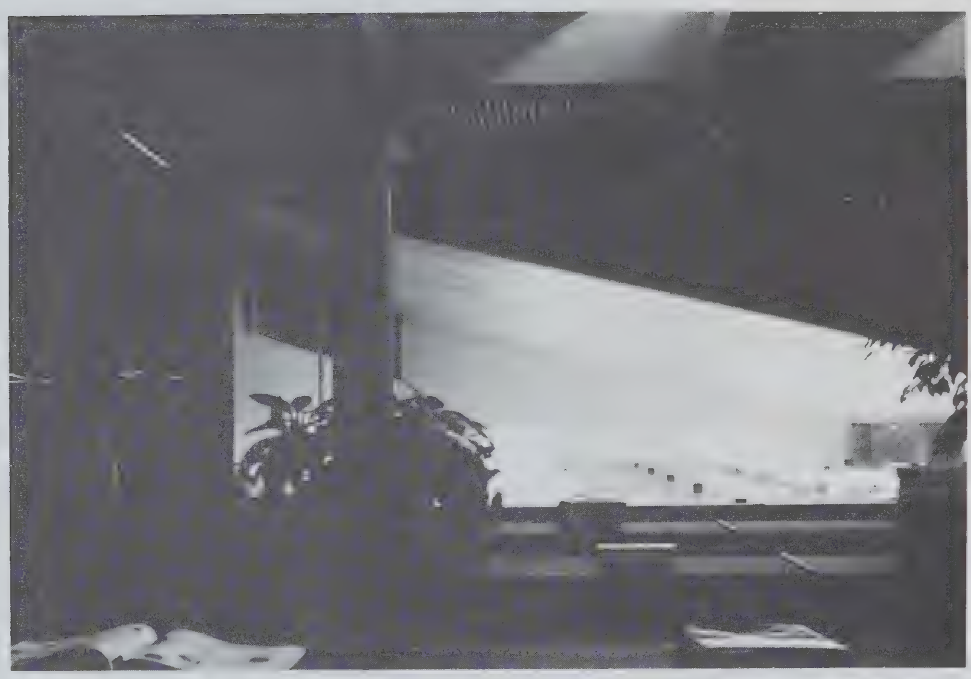


Figure 11. Lending and work area, looking toward stacks, electric light only

Magazine Area

Occupant Response

With its high glazing and many windows, this is the space with the most glass per floor area. The venetian blinds are necessary for both visual and thermal control. They were meant to be operated for their insulating effect on winter nights, to be pulled down and closed during unoccupied hours, and pulled up during daytime to let light and heat in. In summer it was intended that the occupants should shield themselves from overheating and excessive glare when desired. But the blinds were left in one position during the entire winter visit, pulled down and tilted horizontally. In the summer they were pulled all the way up and never used for glare control or prevention of overheating. No person, staff or patron, ever touched the blinds during the two weeks of observation. According to the interviews the occupants never use the blinds but the staff does operate them occasionally, almost seasonally. The blinds were left down and tilted horizontally as a compromise between insulating and daylighting, because the staff did not remember to pull the blinds every day. Unfortunately, the blinds in that position are ineffective for both purposes.

This is the area most frequented by the visitors for seating and there are nearly always people reading here. The daily newspapers and the magazines, in conjunction with the popular paperbacks located here, attract the larger part of the visitors. Also, people were observed coming with books from the stacks to sit and read in the comfortable furnishings.

Most people were observed to seat themselves with their backs towards the windows so that the light fell on their readings and they were shielded from the direct glare.

The task lights are often used after dark and sometimes during daylit hours as well. Since the ambient lights overhead are quite high in this sunken area, the resulting light levels are not sufficient after dark, and almost everyone sitting here in the evening has a task light on.

The visitors followed a pattern of keeping the task lights on as they left if they were already on when they arrived. Interviews verified this, and the visitors explained this behavior with the philosophy that the next person would also need the light. That was the same response that visitors gave if they had been the one to turn the lights on and then left without turning them off. However, an impressive majority of the visitors did turn the lights off.

Visual Comfort

Even though this is a space with a large amount of glass, the dynamic exterior illumination affects the interior illumination relatively little, since the shading and lightshelves are well designed (Figure 12) and all incident light is well distributed due to the exterior and interior reflective surfaces. This results in acceptable luminance ratios and eliminates the glare potential of a room with as much glazing as this one. Even facing south across the space from the adjoining work area, with a view of the entire south portion of the building, the luminance ratios (Figure 13) are generally within the I.E.S. recommendations. The darkest area in the field of view is

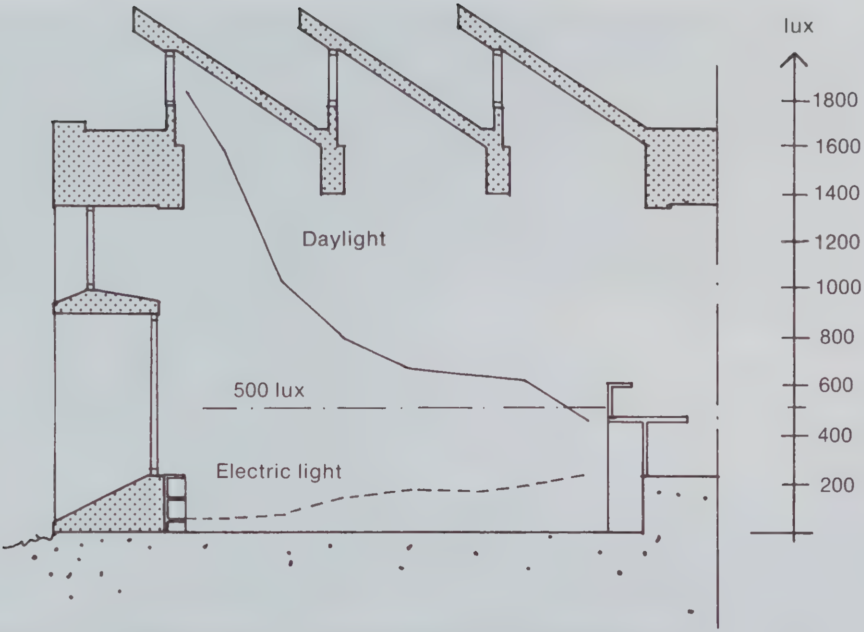


Figure 12. Magazine area, section through south-facing wall

a sequence of dark book bindings on the bookshelves by the work table, at 0.08 only slightly below the recommended minimum of 0.1 times the task luminance. The major exception to the maximum recommendations is the portion of the large south window giving a view of the sky, but that can be mitigated with the venetian blinds. Even other parts of the window, screened by the large plants that thrive in the magazine area, are within the I.E.S. recommended maximum of 10 times the task luminance.

This distribution of luminance ratios was typical of the building. There was generally a comfortable range of luminances, most somewhat lower than the task. The high luminances of upper, sky-facing sections of windows are difficult to avoid with large open spaces and high windows. However, the occupants, exercising the flexibility of seating possibilities and occasionally using the blinds, succeeded in avoiding this difficulty.

Another observation is that the large windows provide distant focus for the eye. When focusing on distant objects, the muscles controlling the eye relax, reducing the potential for fatigue.

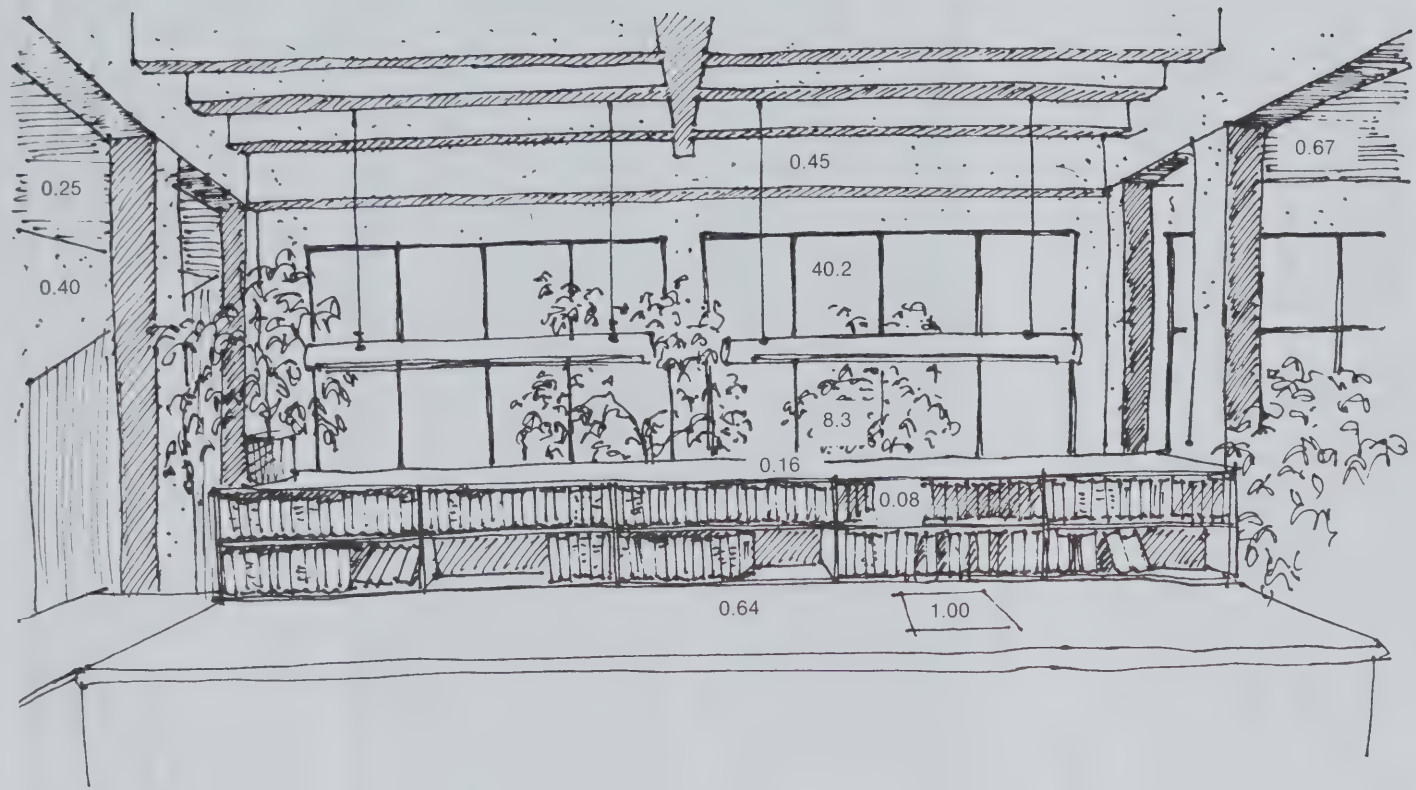


Figure 13. Luminance ratios, facing south from work area

Visibility

Many of the magazines read in this space have very glossy paper, which in this environment sometimes reflects the brightness of the luminaire or exterior light toward the eye, causing veiling reflection. Contrast, and thus visibility, is then reduced. Experimentation with magazines in the space indicates that the reading material can be tilted at different angles to the location of the light source and the eye to avoid such reflections. Patrons were observed to change the tilt of their readings to avoid such loss of visibility.

Stacks

Occupant Response

This is an area that produces many occupant complaints about the low light levels. A majority of the respondents, staff and visitors, agree that the light is rarely sufficient here. Nevertheless, on clear, sunny days in the middle of the day, the lights often remain off. Since the switches are placed at three locations (by the handicap ramp, by the stairs, and by the northern bookshelf) there is often confusion about the correspondence of controls to lights. No information is provided, and the visitors rarely turn on any of these lights. It is probable that if the switches had been placed at each stack, the lights would be more easily and efficiently operated at the location where needed. Every afternoon the returned books are placed back on the shelves. It was observed that except for some sunny and clear days, the lights were turned on by the librarians then. If no visitors were strolling among the stacks, the lights usually were turned off again as the librarians left.

Visual Comfort

There is no glare in this fairly dark space. The luminance ratios are lower than anywhere else in the library, and the different backs of the books make it difficult to show any representative luminance distribution. The two major surfaces measured are the fabric-covered sides of the stacks and the tile floor that have a ratio of 1.6:1. The overall impression of the luminance ratios is that the balance between the surfaces is good and the daylighting is comfortable, even though it is insufficient, especially for the lower shelves.

When the electric lights are turned on, the brightness of the sloped ceiling can in some areas be uncomfortable because it is relatively specular and causes highlight effects. Because of the tilt of the ceiling, it appears as a larger portion in the visual field from some locations; since the space is at the lowest part of the three different levels, the ceiling is a major surface even from a distance in the adjacent spaces. This is a result of the lack of visual and physical partitions. The difference between the reflections from the daylight and the electric light is shown in Figure 14. Since the ceiling is intended to work as a secondary light source, reflections from its surface contribute to the illumination levels below. The pictures show that the contribution is more extensive in the electrically lit situation.

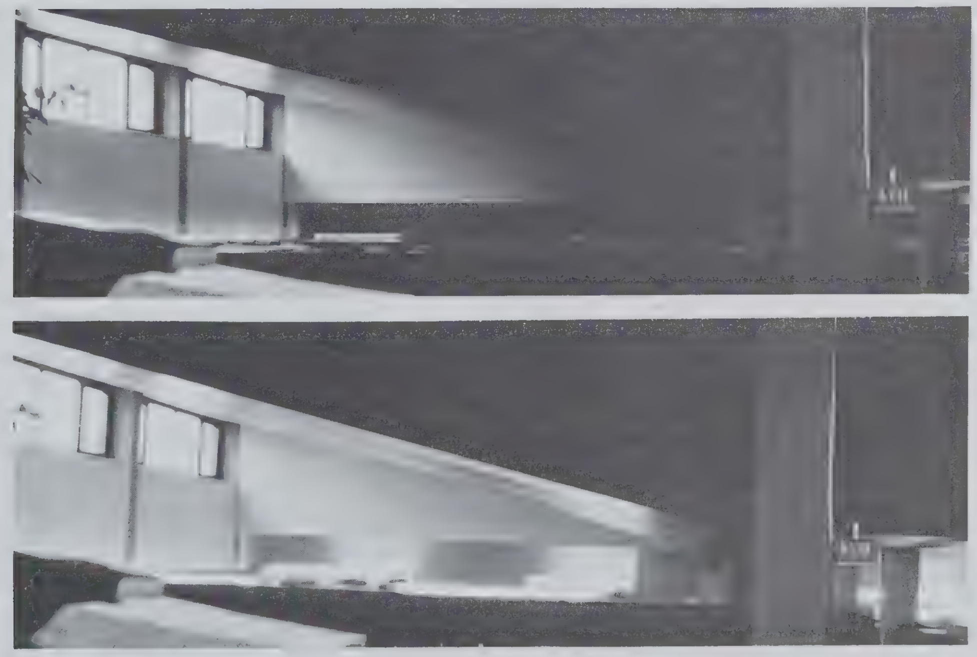


Figure 14. Northern ceiling in stacks, above—daylight only; below—daylight and electric light

Visibility

The visibility is poor because of low daylight levels in this space. The daylight provided by the center clerestory does not penetrate to any depth. The electric light distribution is a good complement; and looking at the curves in Figure 15, a perfect match can be seen

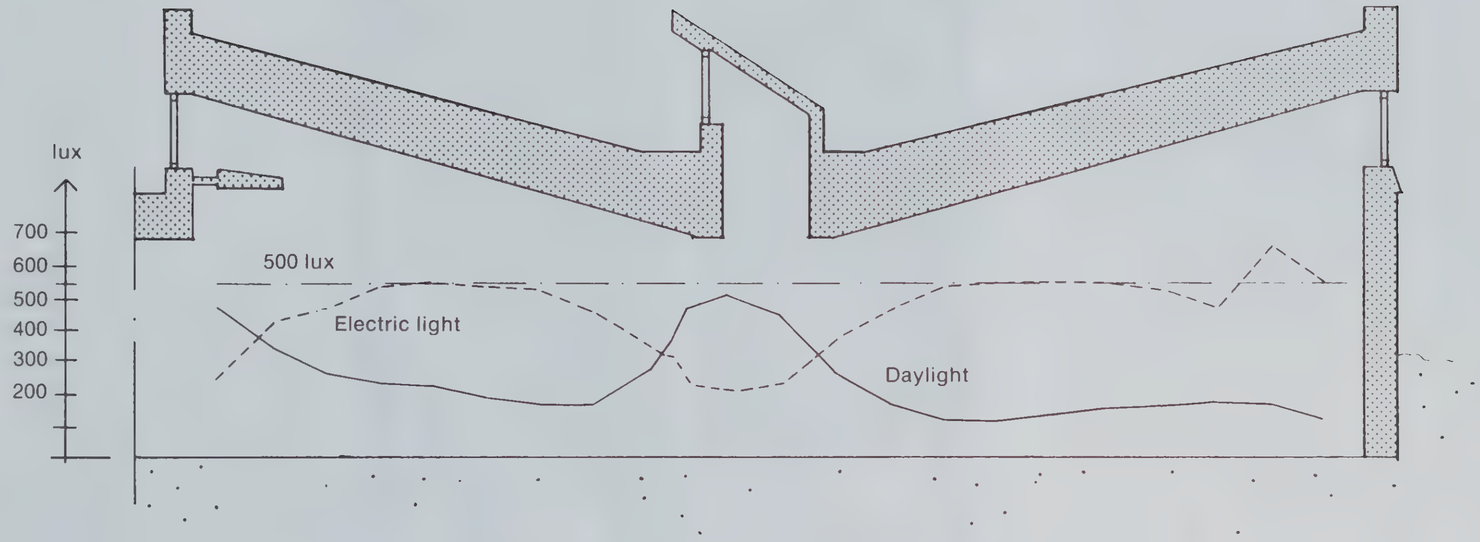


Figure 15. Stacks: electric light and daylight distribution, summer

between the two, which together provide even distribution of light. In the circulation areas there is sufficient daylight; the problem is between the stacks, an expected effect since the shelves work as partitions cutting off potential light distribution by their height.

The additional up-facing fluorescents improve the visibility insignificantly, while having a detrimental effect on visual comfort, mainly in adjacent spaces, because they are not sufficiently diffused and appear in the field of vision from the magazine area and the lending and work areas (Figure 11). The illuminance difference due to these lights between two shelves at standing eye level is as little as 40-45 lux (3-4 footcandles), with the up-facing lights on to complement the down-facing fluorescents.

We did not take pictures of the standard task here because most of the reading from the shelves is done vertically, at different heights. We took a set of pictures of the backs of the books through the center of the space from north to south, to represent the contrast rendition in daylight. As we can see from the photographs (Figure 16), there is a problem with the glossiness of some of the books, since it produces veiling reflections and reduces visual acuity. However, most evident are the differences in light distribution affecting the visibility at different shelf heights.

CONCLUSIONS

The daylighting system has been successful according to visitors and staff; it exceeds expectations from a lighting energy point of view and has been well received in terms of visual quality. A number of specific conclusions are well supported by the evidence presented in this paper.

- For the daylighting systems in this building, toplighting works better than sidelighting because of more easily controlled distribution of light and the elimination of glare under the baffled roof apertures.
- The design and size of the apertures in this building (26% of the floor area) are adequate in almost all cases, except for the stack and children's areas, so that diffuse light from the sky generally provides adequate interior illuminance levels even under most overcast conditions.

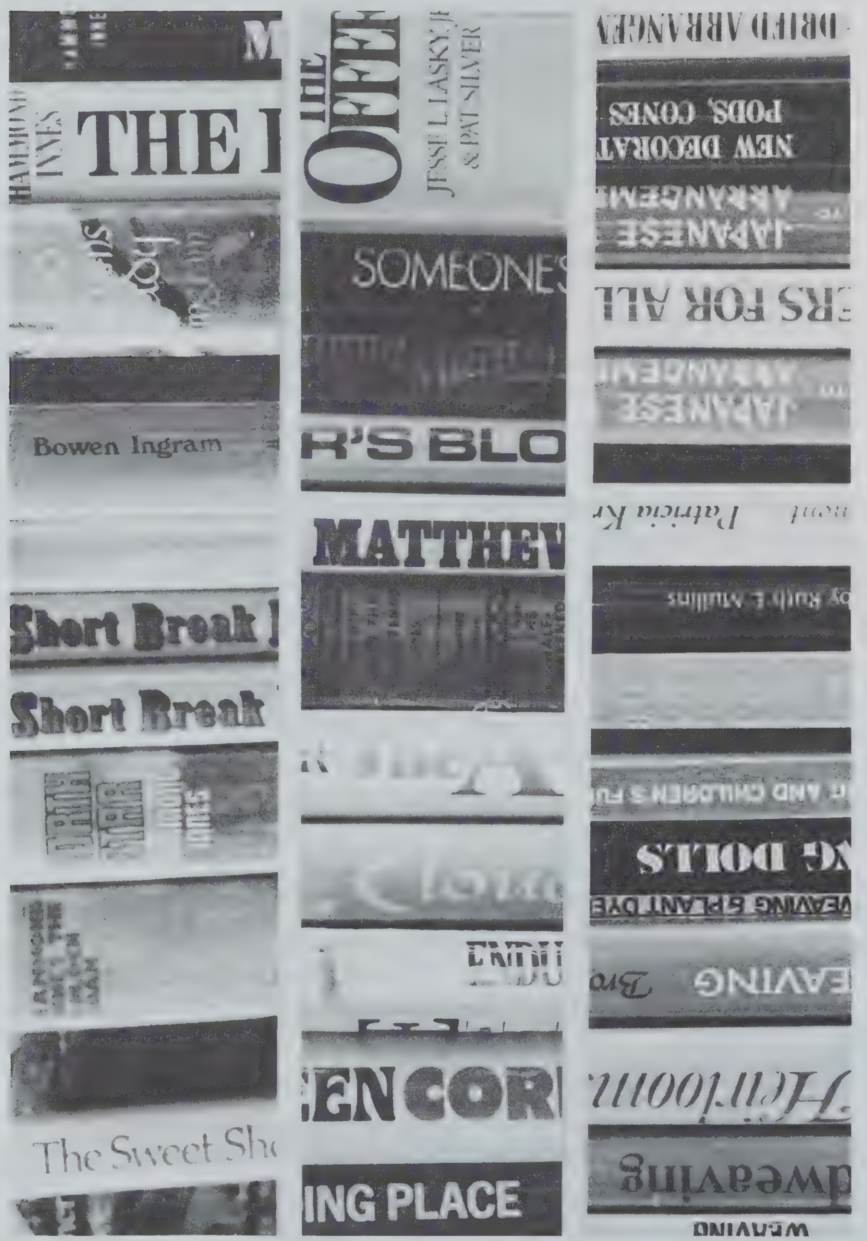


Figure 16. Stacks: books at different heights, daylight

- The roof apertures over the center section of the library are the most successful configuration with highly uniform illuminance both summer and winter because of close aperture spacing, the open space plan, light-colored diffusing surfaces, and avoidance of penetration of direct beam through the use of diffusing baffles.
- Glare is not a significant problem. Although luminance ratios exceeding I.E.S. recommendations are observed in association with view glazing, the occupants do not perceive it as a problem. Reflection of light onto diffusing surfaces is largely responsible for the lack of glare.
- Control elements invite different levels of participation. Task lights are used effectively by both visitors and staff, ambient electric lights are controlled through on/off switches only by the staff, and shading manipulation is greatly restrained on the part of the staff. The latter two are considered by visitors to be too "public" to be controlled by them.
- The staff exercise some control over shading according to their misconception of its purpose, and lack of motivation, since they don't use these areas. Better information provided to both staff and visitors about the intended levels of control could improve the situation.
- Patrons finding a task light on when they arrive will use it but will not turn it off when they leave. There is an assumption that the conditions which exist when they arrive are the "correct" conditions.

The study also suggests additional conclusions.

- Based on interviews, questionnaires, and through their actions, occupants strongly prefer daylighting over electric lighting; daylighting was considered "pleasant," electric lighting "cold." This could be the result of the color or dynamics of the light, or of the method of distribution.
- The relatively large roof glazing area appeared to be an important element of the success of the on/off lighting controls. They provide sufficient light for long periods during most days.

Results from this study also lead to some speculations about reasons for the success of the daylighting system. These should be investigated further.

- The generally good contrast rendition may account, in part, for the acceptance of illuminance levels below traditional design levels.
- Occupants are moving around the library for the more demanding tasks, which is made possible by the open plan that invites flexibility in use.
- Traditional design illuminance levels may be too high (Clear and Berman, 1982).

ACKNOWLEDGMENTS

This work was supported by the U.S. Department of Energy, Assistant Secretary for Conservation and Renewable Energy, Office of Solar Heat Technologies, Passive and Hybrid Solar Energy Division, under Contract No. DE-AC03-76SF-00098.

For their assistance and advice on this project, we would like to thank Kevin Whitley, Ron Kammerud, Moji Navvab, Eliyahu Ne'eman, Michael Wilde, Bruce Corson, Min Kantrowitz, Ed Arens, Gary Morgan, and City Engineer John Vest and the staff and visitors of the Mt. Airy Library.

REFERENCES

Adegran, M., B. Andersson, P. Albrand, T. Webster, and R. Kammerud, 1984. *Total Building Impacts of South-Facing Roof Apertures.* LBL-17562. Berkeley, CA: Lawrence Berkeley Laboratory. Also in *Proc. Windows in Building Design and Maintenance* (June 1984). Göteborg, Sweden: Swedish Council for Building Research, pp. 209-214.

Adegran, M., B. Andersson, and W. Place, 1985. *Mt. Airy Library, a Qualitative Study of Daylighting in a Passive Solar Building.* LBL-18527. Berkeley, CA: Lawrence Berkeley Laboratory.

Andersson, B., M. Adegran, T. Webster, R. Kammerud, and W. Place, 1983. *Thermal Effects Resulting from Occupant Behavior and Building Operation.* LBL-16738. Berkeley, CA: Lawrence Berkeley Laboratory. Also in *Proc. Passive and Hybrid Solar Energy Update* (Washington, DC, Sept. 1983). Washington, DC: U.S. Department of Energy, pp. 121-127.

Andersson, B., M. Adegran, T. Webster, W. Place, R. Kammerud, and P. Albrand, 1984. *Effects of Daylighting Options on the Energy Performance of Two Existing Passive Commercial Buildings.* LBL-18069. Berkeley, CA: Lawrence Berkeley Laboratory. Also to be published in *Building and Environment*, 1986-87. Oxford: Pergamon Press. Also in *Proc. Solar Buildings* (Washington, DC, March 1985). Washington, DC: U.S. Department of Energy, pp. 257-265. Also in *Proc. Summer Study on Energy Efficiency in Buildings* (Santa Cruz, CA, 14-22 August 1984). Washington, DC: American Council for an Energy Efficient Economy, pp. D165-D179.

Andersson, B., M. Kantrowitz, P. Albrand, T. Webster, M. Adegran, and R. Kammerud, 1985. *Effects of Occupant Issues on the Energy Performance of Two Existing Passive Commercial Buildings.* LBL-18398. Berkeley, CA: Lawrence Berkeley Laboratory. Also to be published in *Building and Environment*, 1986-87. Oxford: Pergamon Press.

Clear, R., and S. Berman, 1982. *The Integration of Visual Performance Criteria into the Illumination Design Process.* Presented at the Public Works Canada Symposium (Ottawa, Canada, Jan. 1982).

DOE, 1983. *Passive Solar Commercial Buildings Program Case Studies.* DOE/CE-0042. Washington, DC: U.S. Department of Energy.

Gordon, H., and W. Fisher, 1982. The DOE passive solar commercial buildings program: performance evaluation. *Proc. of the Passive and Hybrid Solar Energy Update* (Washington, DC, Sept. 1982). Washington, DC: U.S. Department of Energy.

Gordon, H., and T. Kurkowski, 1983. Daylighting aspects of the DOE Passive Commercial Buildings Program. *Proc. International Daylighting Conf.* (Phoenix, AZ, Feb. 1983). Washington, DC: U.S. Department of Energy.

I.E.S., 1981. *I.E.S. Lighting Handbook, 1981 Applications Volume.* New York: Illuminating Engineering Society.

Ne'eman, E., 1984. A comprehensive approach to the integration of daylight and electric light in buildings. *Energy and Buildings* 6:97-108.

Ne'eman, E., G. Sweitzer, and E. Vine, 1984. *Office Worker Response to Lighting and Daylighting Issues in Workspace Environments: A Pilot Survey.* LBL-15628. Berkeley, CA: Lawrence Berkeley Laboratory.

Place, W., P. Coutier, M. Fontoynont, R. Kammerud, B. Andersson, F. Bauman, W. Carroll, T.C. Howard, A. Mertol, and T. Webster, 1983. *The Predicted Impact of Linear Roof Apertures on the Energy Performance of Office Buildings.* LBL-16782. Berkeley, CA: Lawrence Berkeley Laboratory.

APPENDIX

INTERVIEW FORMS

Interview Form- Visitors

Sex and age:
Sky condition:
Location:
Date and time:
Illuminance:

1. How often do you come here?
    - For what activity?
    - What time of the day?
2. What do you think about the building?
3. How would you describe the lighting here right now?
4. If you have been here at night/day, how is the lighting different then?
5. Have you thought about why the building is designed as it is?
    - Is there something you would like to see different?
6. Have you noticed any visibility problems anywhere?
7. Would you turn on the lights if you needed them?
    - Would you hesitate to ask the librarian to turn on the lights?
8. If there is too much glare or it's too dark, would you change the blinds?
9. If you turn on a lamp would you most likely turn it off when you leave or not?
    - Why?

Interview Form- Staff

Sex and age:
Sky condition:
Location:
Date and time:
Illuminance:

1. What hours do you usually work?
2. How long have you been working here?
3. What is your most common task?
4. Where in the building do you spend most of your time?
5. How would you describe the lighting in here right now?
6. How would you the describe the lighting after dark?
7. Do you know where all the light switches are located?
8. Have you been informed about the lighting and shading operation?
9. Is there someone particular responsible for lighting control?
10. Have you noticed any special visibility problems?
    - Are there any parts of the building with more glare, or uncomfortable light?
11. Do you think about conserving energy when you turn the lights off?
12. Have you thought about the relationship between having lights on and heating the space with those lights?
13. Do you or the visitors operate the task lights?
    - How?

Passive Solar Journal, 3(4), 387-417 (1986)

The Performance of Adobe and Other Thermal Mass Materials in Residential Buildings

David K. Robertson*
New Mexico Research and Development Institute
Albuquerque, New Mexico 87108

Abstract

This paper reviews the history and current status of thermal mass research, and national, state, and local codes with respect to thermal mass; and offers specific recommendations on how best to use thermal mass for energy efficiency and comfort. Much of the material comes directly from the Southwest Thermal Mass Study (SWTMS), an experimental research study on the thermal performance of adobe conducted at Tesuque Pueblo,

---

*Currently with the Property Control Division, State of New Mexico, Santa Fe, New Mexico 87503.

New Mexico, in the early 1980s. The focus is primarily on residential construction, although the theory and most of the recommendations apply to small commercial buildings as well.

INTRODUCTION

Adobe is the indigenous, massive building material of the Southwest. It has been used worldwide for millenia, and some estimate that over half the world's population currently lives in some type of earthen structure (McHenry, 1984).

Adobe is a sun-dried mud brick, typically sized 10 × 14 × 4 in. (25 × 36 × 10 cm) in New Mexico. It can be laid, usually with mud mortar, to make a wall 10- or 14-in. (25- or 36-cm) thick. As a structural material, it has several advantages over wood-frame construction, including sound attenuation, fire resistance, and the rounded, aesthetically pleasing appearance unique to southwestern homes. Among its disadvantages are somewhat higher cost and longer construction time than wood-frame, more difficulty in handling because of its weight, and more difficulty in insulating because of the lack of a cavity in which to place batt (e.g., fiberglass) insulation. For more information on adobe, the reader is referred to a comprehensive book on the engineering and architectural aspects of adobe by McHenry (1984).

In terms of energy-related characteristics, traditional unstabilized adobe is a low-embodied-energy material (McHenry, 1984); that is, less energy is required to manufacture the material (per unit of wall area) compared to many other wall materials. Adobe bricks can be made by hand if necessary, and cured by the sun. Frequently adobe is made on-site, using raw materials from the site, so transportation energy also is minimal. In addition, adobe functions as a thermal storage material.

The storage of sensible heat may be accomplished with high-density building materials inside a building or as part of a building envelope. Such materials, called thermal mass, moderate heat flow through walls; a daily heat pulse on one side of a wall will be significantly reduced and delayed when it reaches the other side. This process also occurs in lightweight walls, but to a much lesser extent.

Mass has the ability to absorb, store, and release heat. In passive solar applications, mass absorbs excess heat when the interior air temperature rises above the mass temperature, stores it, and then releases it when the space temperature drops. This also occurs in conventional (nonsolar) buildings in transition seasons (spring and fall) and in the cooling season. Thus, mass operates as a "thermal flywheel" or stabilizer of interior air temperatures.

THE SOUTHWEST THERMAL MASS STUDY

The Southwest Thermal Mass Study (SWTMS) had its beginnings in the mid-1970s when architect Bill Haney found that the U.S. Department of Housing and Urban Development (HUD) would not permit adobe construction for federally funded Indian housing projects. HUD's reasoning was that uninsulated adobe did not meet HUD's energy efficiency criteria for new construction. If the adobe was insulated to meet the energy efficiency criteria, it then did not meet HUD's cost criteria. Both criteria were based on insulated wood-frame construction. An added wrinkle was that HUD projects had to use the federal Davis-Bacon wage rates, which required that adobe layers (who traditionally are considered semi-skilled) be paid the same as skilled bricklayers. This also increased the cost of adobe construction.

Haney found that no detailed, extensive research had been conducted on the in situ performance of thermal mass in residential construction. Much work had been done on the steady-state performance of building materials to develop steady-state R-values, but analysis of the dynamic heat transfer characteristics of massive materials, under actual conditions and over the long term, had not been done.

With the then New Mexico Energy Institute (NMEI) at the University of New Mexico, Haney prepared and submitted a proposal to HUD, the U.S. Department of Energy (DOE), and other federal, state, and local governmental agencies to construct and operate an adobe research facility. Coincidentally, DOE was starting up a thermal mass research program, operated through Oak Ridge National Laboratory (ORNL).

The proposal was accepted, and HUD funded the construction of the facility, DOE funded the research, the Eight Northern Indian Pueblos Council and the Pueblo of Tesuque donated the use of the land and an instrumentation building, and the New Mexico Energy and Minerals Department funded development of the technical reports through the state's Energy Research and Development Program. The project was conducted by the staff of NMEI, with assistance from several consultants and oversight by the DOE Thermal Mass Review Panel. A parallel experiment funded by DOE was conducted by the National Bureau of Standards (NBS). The NBS experiment was also overseen by the Thermal Mass Review Panel, which met three times each year for the duration of the project and included representatives of industry, government, and the research community. The adobe industry was represented at panel meetings by Tom Harley of Hans Sumpf Company of Fresno, California.

THE RESEARCH FACILITY

In 1980 and 1981, the facility was built and instrumented at Tesuque Pueblo, 12 miles north of Santa Fe, at a latitude of 35.8° and an altitude of 6330 ft (1930 m). The climate is relatively sunny and cold with heating degree-days of approximately 5800°F day (3200°C day), base 65°F (18°C). Annual average insolation at the site is approximately 1800 Btu/ft^2 day (5.7 kWh/m^2 day) on a horizontal surface. The facility consists of eight simple and well-instrumented test buildings, sized 20 × 20 ft (6 × 6 m) and 8-ft (2.4-m) high (Gustinis and Robertson, 1981). The floors are slab-on-grade with 2 in. (5 cm) of rigid polyisocyanurate on the inside surfaces. Four types of construction are used--adobe, concrete masonry units, milled log, and insulated wood-frame--including five adobe buildings with solid walls of thicknesses of 10, 14, and 24 in. (25, 36, and 61 cm) and both traditional and stabilized bricks (Figure 1). At first the buildings were constructed to be thermally uncomplicated (no windows or doors, heavily insulated ceilings and floors, uninsulated adobe walls, and very low air infiltration rates) so that the behavior of the walls could be isolated and easily measured and understood. Later, windows were added to all but one of the buildings, and one of the adobes was also insulated.

Temperatures and heat fluxes were measured and collected by a Doric datalogger, stored on floppy disks, transferred to magnetic

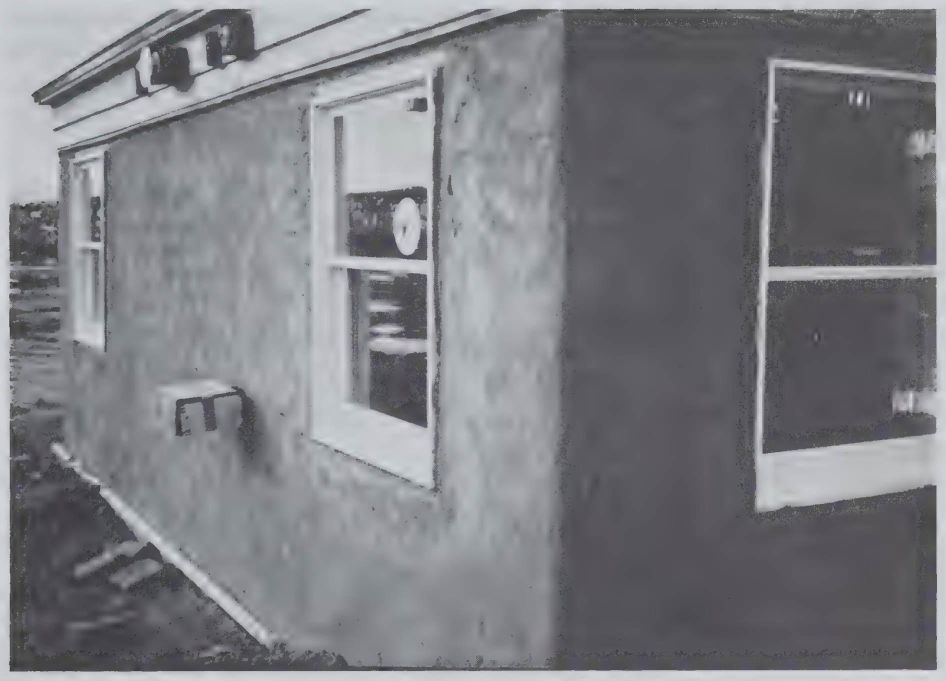


Figure 1. Southwest thermal mass study test building. This is an uninsulated 10-in. (25-cm) adobe building after windows were added.

tape, and then plotted, reduced, and analyzed. Building heat flows were summed, and energy balances were performed. Energy balances were generally accurate to within ±10%; that is, the sum of all measured heat flows for a building (walls, floor, ceiling, infiltration, and solar gain) was within 10% of the heating energy use measured for each building. That is good agreement for an experiment using buildings constructed with normal building methods and materials. The results are presented in two reports (Gustinis and Robertson, 1984; Robertson, 1984).

THE QUESTIONS

The primary question that the researchers wanted to answer was: If you had two conventional (nonsolar) buildings, one lightweight (wood-frame walls) and one massive (adobe walls), otherwise identically constructed and insulated, what would be the difference in space heating and cooling energy consumption over the course of a year? This is what is commonly referred to now as the "thermal mass effect." The researchers acknowledged that the measured energy use differences would only be valid for that particular building configuration (e.g., shape, orientation, window area, number of rooms) and for the climate in which the experiment was conducted, in this case northern New Mexico.

Additional questions posed were: What is the in situ steady-state R-value of adobe? What does thermal mass do and how does it work?

RESULTS OF THE SOUTHWEST THERMAL MASS STUDY

Steady-State R-Value

The steady-state conductive (surface-to-surface) R-values of adobe were calculated using long-term averages of wall heat flow and surface-to-surface ΔT. Including the 0.5 in. (1.3 cm) of mud plaster on each side of the walls, the R-values (in units of h ft^2 °F/Btu) were: R-2.0 for the 10-in. wall, R-2.7 for the 14-in. wall, and R-4.4 for the 24-in. wall (in units of m^2 K/W, RSI-0.35 for the 25-cm wall, RSI-0.48 for the 36-cm wall, and RSI-0.78 for the 61-cm wall). These were for well-cured, in-place adobe walls, with moisture content (by weight) less than 2% for the thinner walls and 3% for the 24-in. (61-cm) walls. No measurable difference in thermal conductivity was found as a function of these levels of moisture content, and the conductivity of the fully stabilized adobe walls was only slightly higher (by a few percent) than the traditional (nonstabilized) adobe walls. Experimental error for the R-value measurements was estimated as ±11%.

Note that these values are steady-state R-values only and do not include the dynamic "thermal mass effect," which is discussed below. Also, these values are specific to the particular adobes used, which were from the San Juan Pueblo adobe yard near Española, New Mexico, and which had a density of approximately 117 lbm/ft^3 (1870 kg/m^3). The density of adobe can vary from 90 to 120 lbm/ft^3 (1440 to 1920 kg/m^3); the R-value would be higher for lower-density bricks.

Some disagreement exists about the R-value of adobe. Variation in the properties of the raw material thermal properties may explain this. However, even if the R-value of adobe is twice what is given above, adobe is still a poor insulator, and exterior walls should be insulated to be energy-efficient. Furthermore, for passive solar applications, the high conductivity (low R-value) of adobe is actually desirable, because heat can be readily absorbed, stored, and released in the daily solar cycle--if exterior walls are well-insulated on the outside.

Reputation of Adobe

If the R-value of adobe is so low, why then does uninsulated adobe have such a good reputation for energy efficiency and comfort? Part of the answer to this question lies in the ability of adobe to moderate weather extremes. However, there may be other, more subjective reasons.

Imagine you lived in adobe homes all your life, probably heated with wood, and in the early 1970s you were given a new gas-heated, wood-frame HUD home. Assume the new home was minimally insulated and not very tightly constructed. Your initial reaction might be that it is a foreign type of construction, not aesthetically pleasing with its straight lines and flat surfaces, and it probably would not withstand the centuries of use your old adobe has. It heats up quickly on summer days and does not maintain an even temperature. In winter, you have to keep the furnace going all night, whereas your old adobe had been absorbing the radiant heat from your wood heating system all evening and would probably make it until morning without another fire. And, to top it all off, you are periodically presented with a large heating fuel bill, whereas the wood you used to heat your adobe house was essentially free, requiring only labor to cut and haul.

You conclude that your old adobe is more comfortable, does not require continuous heating, costs less to heat, and requires no cooling. Many of these observations have some technical merit, but they do not fully offset the lack of insulation.

Wall Heat Loss

The question of how thermal mass in a building envelope performs, and what its heat transfer characteristics are, can best be answered by a graphic presentation of wall heat flow. The plots in Figure 2 are based on SWTMS results and other research conducted as part of the DOE Thermal Mass Program. The plots demonstrate the effects of mass and insulation on heat flow through a wall.

The assumptions are that it is midwinter (the wall is continuously losing heat), and the interior air is thermostatically controlled to a

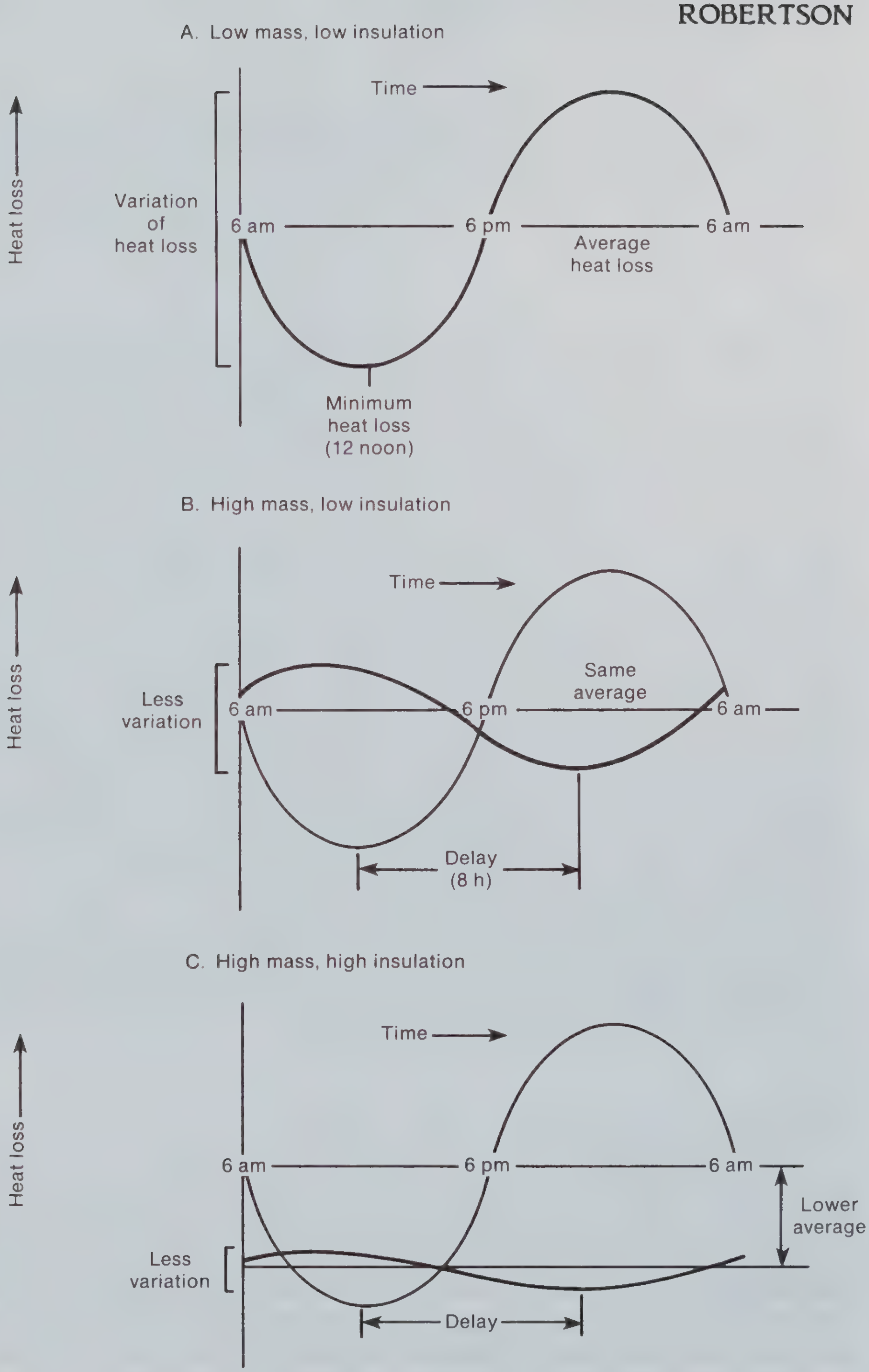


Figure 2. The effects of mass and insulation on wall heat loss. Note that mass reduces variation of heat loss and delays the timing of heat loss, and that insulation reduces the average heat loss. The lighter curves in B and C are the A curve shown for comparison.

near-constant temperature. The outside surface of the wall is exposed to a sol-air temperature that varies sinusoidally. (Sol-air temperature does not vary sinusoidally in reality, but a sine curve was used to provide a clear conceptual understanding.) Mass is located *inside* the insulation layer in these cases.

Each of the three plots in Figure 2 is a heat-loss-versus-time curve. Heat loss is on the vertical axis, with increasing heat loss toward the top. Since it is midwinter and the walls are losing heat continuously, heat gain is not present on any of the plots. The horizontal axis is time, from 6:00 am to 6:00 am over a 24-h period, increasing to the right. The horizontal line on each plot denotes the average heat loss for the curve.

The first curve (A) shows the hour-by-hour heat flow response of an idealized base-case wall with very low mass and very low R-value. At 6:00 am, as the sun comes up and the outside temperature begins to rise, the wall heat loss starts to decrease. At noon, when the outside temperature is at a maximum, heat loss is at a minimum. Similarly, when the outside temperature drops to its lowest at midnight, that is the time of greatest heat loss. Both return to their original value at 6:00 am the next morning.

The pattern of heat loss in curve A is similar to the behavior of an uninsulated wood-frame wall. (Under actual conditions, outside temperature peaks at around 2:00 pm and drops to a minimum just before sunrise.) Such a wall would show some change in the shape and timing of the curve; it would not follow the outside temperature profile exactly.

The second curve (B) shows the heat loss of an idealized wall if mass, but no insulation, were added to the low mass/low insulation wall in A. The curve for the massive wall is the heavy line, and the curve for the low mass/low insulation wall in A is shown for comparison by the lighter line. Since insulation has not been added, and the mass is assumed to have no R-value in this example, the average (and total) heat loss is the same as for the first wall. However, there are two important effects of the mass. First, it produces *less variation* in the heat flow: the difference between the maximum and minimum is smaller, showing that the mass moderates the extremes. In addition, the mass *delays* the timing of the maximum and minimum, shifting the whole curve to the right. Thus, whereas the minimum heat loss in a massless wall occurs exactly at the time of the highest outside temperature, it occurs several hours later in a wall with mass.

This curve is similar to the behavior of an uninsulated massive wall, such as 10-in. (25-cm) adobe. Such an adobe wall produces approximately half the variation in heat loss as the uninsulated frame wall in A, and the delay is approximately 7-8 h. Delays for thicker adobe walls are 10 h for 14 in. (36 cm) and 18 h for 24 in. (61 cm), with coincident reductions in variation of heat flow. These time lags were determined experimentally in the SWTMS. [See the discussion in the later section "Other Thermal Mass Research" and Childs (1983) for a more theoretical discussion of the time lag.]

The third curve (C) shows the behavior of an idealized wall with both mass and insulation. Note that the two effects of mass discussed earlier are present: *less variation* (amplitude) of heat flow and *delay* (time lag) of heat flow. Here, the variation is further reduced by the presence of insulation. In addition, the primary effect of insulation is present: the rate of heat loss is always *reduced*. Thus the average heat loss (and the total heat loss for the 24-h period) is reduced. This curve is similar to the behavior of a well-insulated 10-in. (25-cm) adobe wall. Thus, with a combination of interior thermal mass and exterior insulation, the benefits of both can be achieved. These results are not climate-specific.

Building Heat Flow

These two effects of thermal mass--moderation and delay of heat flow--have important implications for space heating and cooling energy consumption, particularly as the mass interacts with other building elements and the space-conditioning system. The most significant implication is the moderating influence of thermal mass. When heating (or cooling) is required continuously throughout the day, mass has no effect on energy use. However, when a building experiences alternating periods of net energy loss and net energy gain during each day, thermal mass will save energy. This is the case in most of New Mexico in spring, summer, and fall, and in buildings with high solar gain in winter.

To see how this works, look at Figure 3. This is a curve similar to those in Figure 2, with two important differences. First, the heat flow for the total building, not just the walls, is shown. Secondly, due to the time of year (or appropriate combinations of insulation and solar gain), the average heat loss for the building is zero. When the curves are above the line, the building is losing heat, and when the curves are below the line, the building is gaining heat. The total gain for the day equals the total loss for the day. Again, these are idealized curves, and these exact conditions rarely if ever occur.

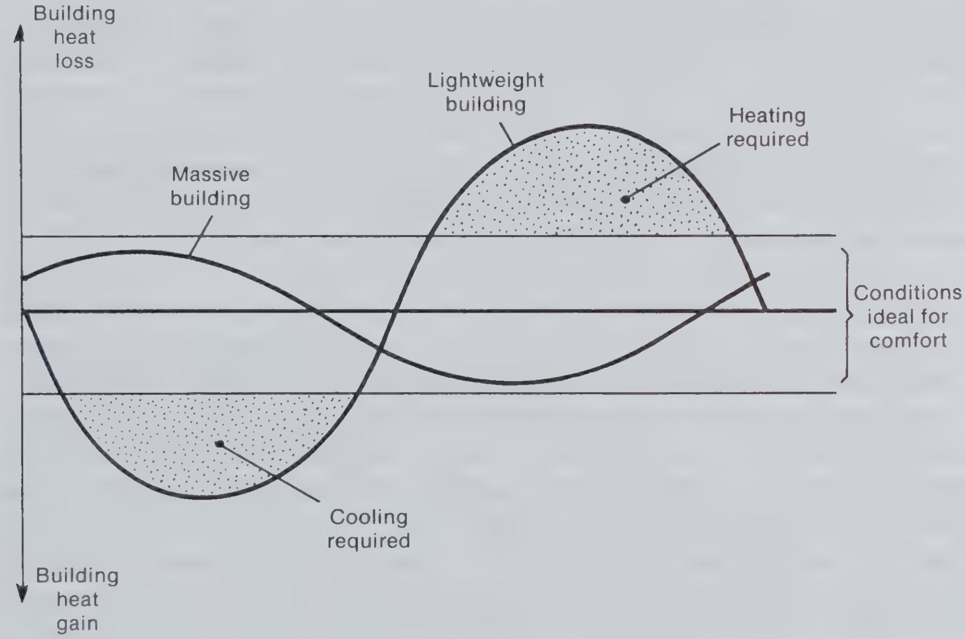


Figure 3. **Daily building heating and cooling loads. Under certain conditions, a massive building might require no space conditioning, whereas a lightweight building with similar insulation levels might require both heating and cooling over the course of a day.**

Whereas the lightweight building requires cooling for part of the day and heating for part of the day, the massive building requires neither. There are many days in the spring and fall transition seasons and in the summer cooling season when this effect saves energy. It usually does not save both heating and cooling energy on a daily basis, but it saves one or the other.

The delay of heat flow caused by thermal mass can also save energy. Note from Figure 3 that the cooling load for the massive building occurs in the evening and nighttime hours. This timing permits the homeowner to cool the building by ventilating with cooler nighttime outside air. In many if not all cooling season days, this eliminates the need for cooling energy. In a lightweight building, on the other hand, the cooling load occurs in midafternoon, at the hottest part of the day when air conditioners operate at their lowest efficiency and when there is no opportunity for ventilation cooling.

Another benefit of thermal mass, peak load reduction, is apparent from the results. Figure 3 shows that the building heating or cooling load is more constant, and the peak loads are smaller. This will reduce utility peak loads (most importantly for electric utilities), and thus utility capacity requirements; the size and cost of heating and cooling equipment in the building; and, to some extent, the energy consumption of heating and cooling equipment in the building as a result of less cycling.

The magnitude of the thermal mass effect will vary with building configuration, climate, and time of year. At the Southwest Thermal Mass Study, the effect on total heating season energy consumption was 3.5% for windowless test buildings and 5% for test buildings with windows. When the results were extrapolated to the milder climate of Las Cruces, New Mexico, with heating degree-days of 3200°F day (1780°C day) [base 65°F (18°C)], the effect was 12% for test buildings with windows. It is important to note here that, although the percentage savings may vary from climate to climate, the absolute energy savings are often similar.

Funding was not provided for testing in the cooling season, but the effect is expected to be greater because there would be many more days in the season when buildings experience alternating periods of net heat gain and net heat loss on a daily basis. Taking advantage of the delay of mass walls through ventilation strategies further reduces cooling loads.

THE DOE THERMAL MASS PROGRAM

The DOE Thermal Mass Program includes the Southwest Thermal Mass Study and a similar experiment at NBS (Burch et al., 1983).

Christian (1985) gives an overview of the program. The goal of both experimental studies was to develop a detailed and reliable data base on the thermal performance of buildings with various amounts of thermal mass. Once the data were collected, several main-frame building simulation computer models (BLAST, DEROB, TARP, and DOE-2) were used to perform consistency checks on the data. At the same time, computer models were validated to perform extensive and detailed modeling of a prototypical house for a variety of U.S. climates. The researchers assumed that if the computer models could accurately predict the performance of building components, the test buildings' overall energy use, and the magnitude and timing of the thermal mass energy savings for different seasons of the year, then the models could predict those savings for full-size buildings in different climates.

Although numerous organizations (see the section "Other Thermal Mass Research") performed many computer simulations of full-size buildings, the primary work was done by Lawrence Berkeley Laboratory (LBL) (Carroll, Sullivan, and Mertol, 1985), using the program BLAST 3.0. The prototype house modeled was a 1200-ft^2 (112-m^2), single-story, three-bedroom house with typical window area and placement, insulation levels, thermostat schedules, internal loads, and furnishings. An important atypical condition was that the floors and foundations were assumed to be massless. As in the experiments at SWTMS and NBS, this isolated the wall mass effect. The principal parameters varied were climate; wall insulation level and location; and wall thermal mass thickness, density, and thermal conductivity. Weather data from six cities were used, representing different climates around the United States.

The results indicate that, for a given wall R-value, annual heating and cooling loads always decrease with increasing mass, regardless of wall type or climate. In some rare cases in very mild climates, energy use actually increases with an increase in insulation [see also Burch et al. (1983)]. Generally speaking, loads decrease more when insulation is placed outside the mass, compared to inside it.

Table 1 presents selected results from the simulations. The table shows the annual reductions in sensible heating and cooling loads when wall thermal mass varies from near zero to a level similar to

Table 1. Selected Annual Sensible Heating and Cooling Load Reduction from BLAST Simulations

Location	Annual Building Load Reduction % (MBtu)[a] Heating		Cooling	
Atlanta, no insulation	10.7	(4.5)	29.7	(8.1)
Atlanta, R-5[b] outside	12.1	(3.0)	24.5	(4.8)
Atlanta, R-20 outside	10.6	(2.0)	19.9	(3.4)
Denver, no insulation	11.8	(9.6)	52.9	(10.5)
Denver, R-5 outside	13.6	(6.4)	40.9	(5.8)
Denver, R-20 outside	12.0	(4.3)	32.0	(4.0)
Minneapolis, no insulation	2.8	(3.6)	35.2	(5.7)
Minneapolis, R-5 outside	3.2	(2.6)	30.2	(3.5)
Minneapolis, R-20 outside	3.0	(2.0)	25.0	(2.6)
Phoenix, no insulation	39.5	(7.4)	16.7	(11.3)
Phoenix, R-5 outside	38.2	(3.6)	11.5	(5.5)
Phoenix, R-20 outside	31.6	(2.1)	8.5	(3.6)
Washington, no insulation	7.0	(4.7)	36.4	(7.9)
Washington, R-5 outside	8.1	(3.3)	31.2	(4.8)
Washington, R-20 outside	7.3	(2.3)	25.7	(3.4)

Reductions assume a massless floor and foundation. If concrete slab floors were used in the simulations, these numbers would be considerably smaller (see text).

Assumptions for mass properties: thickness, 7.2 in. (18.3 cm); conductivity, 0.50 Btu/h ft °F (0.86 W/m K); density, 90 $\mathrm{lbm/ft^3}$ (1440 $\mathrm{kg/m^3}$); specific heat, 0.30 Btu/°F lbm (1.2 kJ/K kg); R-value, 1.2 h $\mathrm{ft^2}$ °F/Btu (0.21 $\mathrm{m^2}$ K/W). [For comparison, adobe would be: thickness, 10 in. (25 cm); conductivity, 0.46 Btu/h ft °F (0.80 W/m K); density, 117 $\mathrm{lbm/ft^3}$ (1870 $\mathrm{kg/m^3}$); specific heat, 0.24 Btu/°F lbm (1.0 kJ/K kg); R-value, 1.8 h $\mathrm{ft^2}$ °F/Btu (0.32 $\mathrm{m^2 K/W}$).]*

[a] 1 MBtu = 1.054 kJ

[b] R-1 = RSI-0.176

that of 10-in. (25-cm) adobe (see assumptions in Table 1). The reductions are presented in terms of relative (percent) reduction of total loads, and in terms of absolute annual reduction of total loads, in MBtu. Results are shown for five cities and for three different levels of insulation: none, R-5 (RSI-0.9), and R-20 (RSI-3.5), all on the outside of the mass.*

---

*k = 10^3, M = 10^6; RSI is R-value in the unit $\mathrm{m^2K/W}$.

Note that the percent reductions vary considerably and can be quite high--between 30% and 40%--in mild climates such as the mild heating climate of Phoenix and the mild cooling climate of Denver. The absolute reductions, however, show much less variation. The savings from mass with even higher thickness, conductivity, and density (calculated but not shown here) are greater, but the bulk of the load reductions which are possible has been realized with this level of mass.

Note also that the percent reductions are unrealistically high, because the floors and foundations are assumed to be massless. If floor mass were added to a level equivalent to a 4-in. (10-cm) concrete slab, the mass effects for the prototype house would be 25% less in the cooling season and 75% less in the heating season, on the average, according to calculations by Christian (1985).

The next step in the Thermal Mass Program, currently underway, is to develop a simplified tool that will predict the energy savings from thermal mass for any building configuration and climate, based on computer results such as these. Such a tool would be used by architects, engineers, builders, and code officials for residential design and construction. The tool could be a microcomputer program, a manual calculation, a special energy calculation sliderule, or tables and charts. Some tools have been developed, primarily outside the DOE Thermal Mass Program, and are discussed in the next section.

OTHER THERMAL MASS RESEARCH

Other research in thermal mass has been conducted by numerous industry groups and other DOE research programs. Research by state governments and the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE), primarily with reference to energy conservation building codes, is discussed in the later section on codes.

The industry groups--primarily the National Concrete Masonry Association (NCMA), the Brick Institute of America, and the Portland Cement Association (PCA)--have for many years promoted the energy savings benefits of thermal mass and funded research to document and quantify those savings. One of the earliest methods of accounting for thermal mass was the M-factor, developed by consultants to NCMA with the computer program NBSLD in the mid-1970s (Catani, 1978). The M-factor is a correction to steady-state R-values that can result in less insulation being required in opaque wall sections of massive buildings than for lightweight buildings. Charts of M-factors show the correction as a function of degree-days and weight per unit of wall area.

PCA developed a "delta-R" methodology using the computer code BLAST, which reduces required R-values of wall insulation when thermal mass effects are included.

Arumi of the University of Texas, funded by NCMA and DOE, developed the computer program DEROB to investigate the effects of wall thermal inertia on heating and cooling energy consumption (Arumi, 1977). He used a dimensionless number (gamma) to quantify thermal inertia and developed a manual method to calculate mass effects for various generic wall assemblies. A similar number was later presented by Childs (1983).*

Much of this early work was regarded with suspicion by some members of the building industry, particularly the insulation representatives. However, with the increasing research devoted to thermal mass, including the DOE Thermal Mass Program discussed previously, some degree of agreement is being reached both among the extensive computer simulations and among the various members of the building industry.

Bion Howard, then of NCMA, compiled the results of many of the computer studies done for different building configurations and climate regions (Howard, 1984 and 1985). Based on this compilation, Howard developed the curves in Figure 4. The curves show the approximate percentage reduction that can be expected in conventional (nonsolar) building heating and cooling loads if the building were constructed of masonry walls, as compared to lower mass frame-wall construction. These curves are for buildings with wall mass greater than 35 lbm/ft^2 (170 kg/m^2). [By comparison, 10-in. (25-cm) adobe would be close to 100 lbm/ft^2 (490 kg/m^2).] Actual savings can vary considerably from the curves shown since these curves represent varying amounts of mass above 35 lbm/ft^2 (170 kg/m^2), various building configurations, and different modeling assumptions. The curves show that both the heating and cooling thermal mass effects vary with the mildness of the climate up to 30%-40%.

---

*The behavior of building envelope thermal mass can be quantified by combinations of material properties: density ρ (lbm/ft^3, kg/m^3), thermal conductivity k (Btu/h ft °F, W/m K), heat capacity c (Btu/lbm °F, J/kg K), and wall thickness L (ft, m). The quantity ρcL is a measure of the wall's ability to store energy, and the quantity k/L is a measure of the wall's ability to conduct energy. The ratio of the two $[(\rho cL^2)/k]$ is an indication of the speed at which a temperature profile moves through a wall. The time lag for a single-layer, homogeneous wall is less than or equal to 1/6 of that ratio.

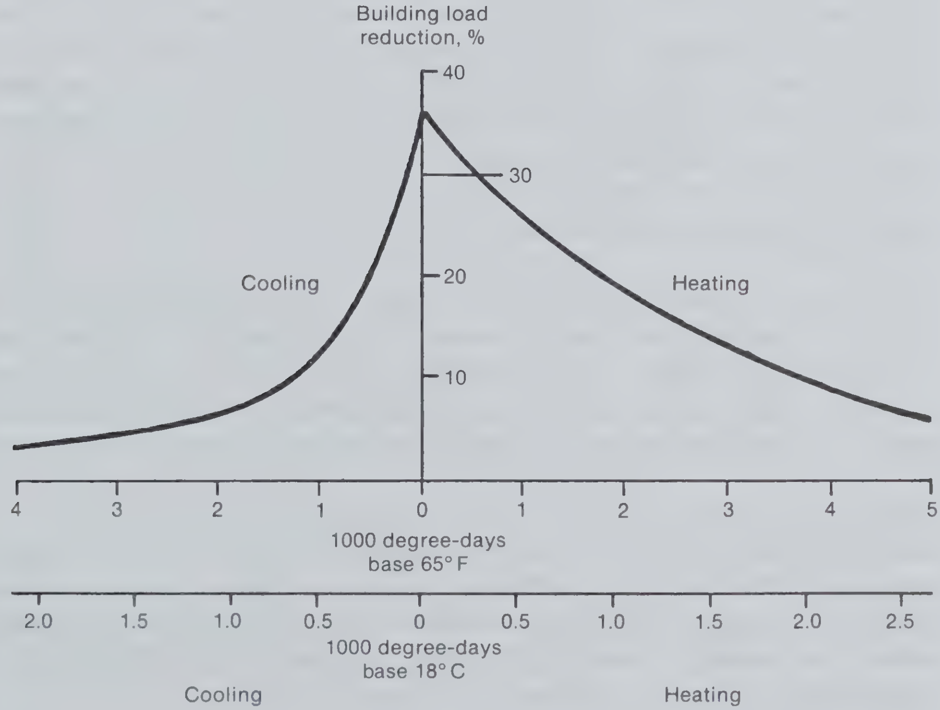


Figure 4. Building energy load reductions for masonry wall vs wood-frame wall. These curves are for walls with 35 lbm/ft^2 (170 kg/m^2) or more. Note that the mass effect is strongly dependent on the mildness of the climate. Source: Howard, 1985

Another DOE research program that includes thermal mass is the Affordable Housing Guidelines (AHG) project (Steven Winter Associates, 1983 and 1985). AHG is an outgrowth of the now-defunct Building Energy Performance Standards (BEPS) program. In this project, a sliderule methodology was developed at LBL, based on a large number of runs of the computer code DOE-2. The sliderule is used to calculate building heating and cooling energy use, based on desired building insulation levels, window area, infiltration rates, climate location, etc. A builder can change various parameters (e.g., ceiling insulation level) and determine the change in energy use.

The initial version of the AHG sliderule and documentation (1983 draft) did not include thermal mass as a parameter that affects building energy use. However, material has been developed to include thermal mass adjustments for masonry and log wall construction (Byrne and Ritschard, 1986). Upon completion, the guidelines will be required for new construction of federal buildings. They will also ultimately find their way into the residential building code standards process of ASHRAE, and hence to state and local building codes and HUD standards.

PASSIVE SOLAR RESEARCH

The research described above is limited to conventional construction, in which window area is usually no more than 15% of the floor area and distributed among all orientations. With the development of passive solar technology in the last decade, there has been a great deal of research on thermal mass in passive solar applications.

The three requirements of a well-designed passive solar system are: 1) a well-insulated, low-infiltration building envelope, 2) solar gain, and 3) thermal mass. Without adequate thermal mass, the best a solar building can do is provide daytime heating; mass is needed to prevent daytime overheating and carry the building through nights and periods of cloudy weather.

Even with sufficient thermal mass, its location, color, thickness, and surface area must be designed to maximize daily heat storage and provide a steady interior environment without excessive temperature swings. This is usually accomplished by establishing the correct ratio of direct gain (daytime heating) and indirect gain (nighttime heating) and maximizing the mass in direct sunlight (radiatively coupled) as compared to the mass heated by room air (convectively coupled). These are entire research areas in themselves.

Perhaps the most comprehensive work to date on passive solar is that of Balcomb and his coworkers at Los Alamos National Laboratory (Balcomb et al., 1984). The Los Alamos group developed correlations of solar performance with building load and solar aperture for numerous reference designs and climate locations, based on extensive computer analysis (using the computer code PASOLE) and test cell monitoring. They developed three levels of manual methodologies to determine solar performance, ranging from rules of thumb to overall annual performance to monthly performance. The methodologies are simple to use and appropriate for various stages of the design process.

The reference designs include varying levels and characteristics of thermal mass. Sensitivity studies were done to assess the effect of various mass parameters on performance. These parameters include thickness, specific heat, thermal conductivity, absorptance, distribution, and surface area. For example, for a residence in Albuquerque with a small heating load, high direct solar gain, and no night insulation, as the thickness decreases from 4 to 1 in. (10 to 2.5 cm), the solar savings fraction decreases from close to 100% to close to 0%. In the terminology of the previous sections, this amounts to a "thermal mass effect" approaching 100%. That is, a high mass solar building of this design would use almost no heating energy compared to a lightweight solar building of the same design.

At present, passive solar and thermal mass are still two separate areas of research but it is likely that they will merge, particularly as conventional housing becomes more and more "sun-tempered." Current computer simulation research at LBL includes quantifying the thermal mass effect as a function of south glass area, from conventional to fully passive solar designs.

BUILDING CODES

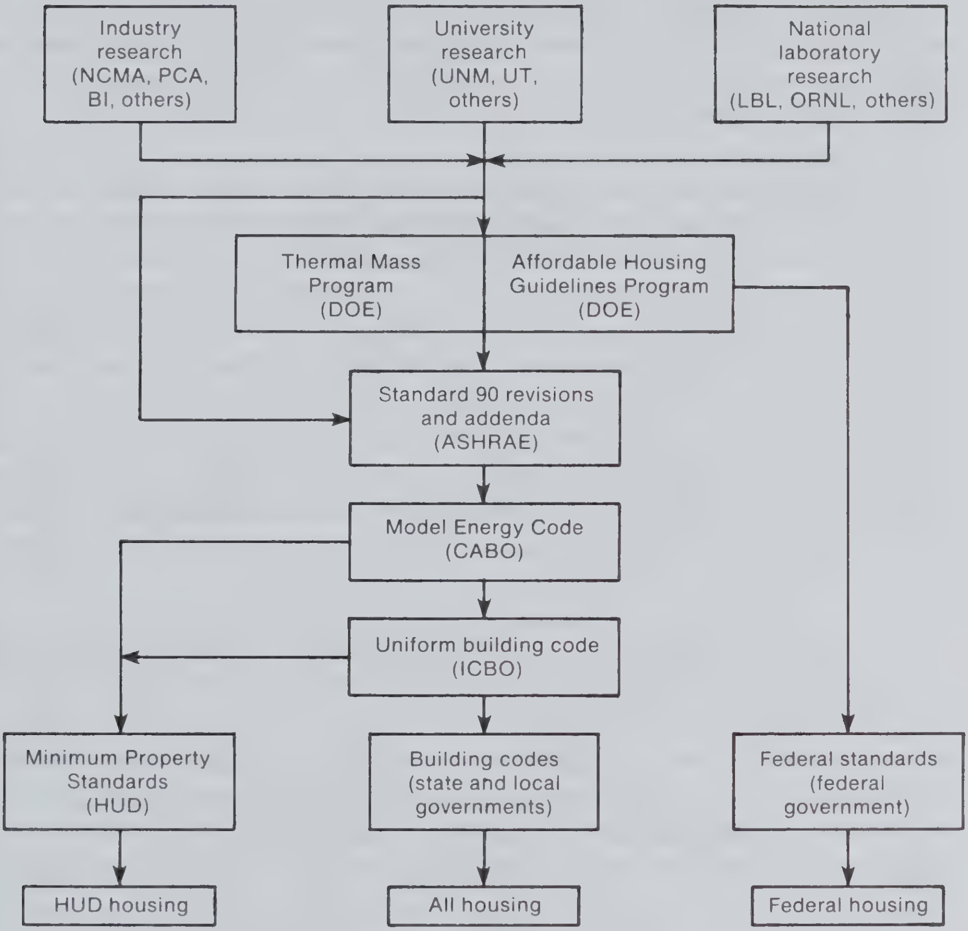
The goal of the research presented above is not only to provide up-to-date technical information to industry and the public, but to provide input to building codes and standards. The complex maze of different and overlapping building codes can be very confusing; the book *Adobe Codes* by Adobe News, Inc., (1985) does a good job of describing current state and local codes.

New construction in the United States is required to conform to building codes. These may be a national code, a state code, and/or a local code, depending on location of the site. Usually the state or local government simply adopts the national code. If the state or local government finds portions of the national code unacceptable, it develops its own and replaces the unacceptable sections of the national code. This is the case with the national Uniform Building Code (UBC) structural requirements for adobe. The UBC required minimum 16-in. (41-cm) wall thickness--New Mexico found this unacceptable and rewrote the section to allow a 10-in. (25-cm) minimum thickness while maintaining a certain thickness-to-height ratio.

If the building is HUD public housing, including Indian housing, or housing financed through FHA, then the HUD Minimum Property Standards (MPS) must be met. Prior to 1985, HUD wrote its own MPS, but since mid-1985 the MPS are based on national codes, or on the state or local codes if they are found acceptable by HUD (HUD, 1985). If the building is a federal building, owned by the federal government and used by a federal agency, it must conform to a different set of federal standards.

The common denominator of most of these codes is the UBC. The energy portion of the UBC is the Model Energy Code, which is based on ASHRAE Standard 90, the ASHRAE standard relating to energy conservation (ASHRAE, 1975 and 1980). It is through the Standard 90 revisions and addenda (ASHRAE, 1985) that research such as that on thermal mass is ultimately incorporated into building codes and HUD Minimum Property Standards. This process is shown in flowchart format in Figure 5.

The ASHRAE Standard 90 was initially developed in 1975 (called Standard 90-75) and specified minimum requirements for energy conservation in new construction. Three methods of compliance were allowed: 1) component (e.g., minimum wall R-values), 2) acceptable practice (e.g., typical wall sections), and 3) systems


Industry research (NCMA, PCA, BI, others)
University research (UNM, UT, others)
National laboratory research (LBL, ORNL, others)
Thermal Mass Program (DOE)
Affordable Housing Guidelines Program (DOE)
Standard 90 revisions and addenda (ASHRAE)
Model Energy Code (CABO)
Uniform building code (ICBO)
Minimum Property Standards (HUD)
Building codes (state and local governments)
Federal standards (federal government)
HUD housing
All housing
Federal housing

NCMA – National Concrete Masonry Association
PCA – Portland Cement Association
BI – Brick Institute
UNM – University of New Mexico
UT – University of Texas
LBL – Lawrence Berkeley Laboratory
ORNL – Oak Ridge National Laboratory

DOE – U.S. Department of Energy
ASHRAE – American Society of Heating, Refrigerating and Air-Conditioning Engineers
CABO – Conference of American Building Officials
ICBO – International Conference of Building Officials
HUD – U.S. Department of Housing and Urban Development

Figure 5. Incorporation of thermal mass research into residential building codes and standards

(e.g., computer modeling of entire building). Many states were reluctant to adopt portions of 90-75 because, for example, passive solar could not comply unless a systems approach, very expensive for individual homes, was used. In addition, there was no credit for wall thermal mass.

The State of New Mexico funded its own research in 1976 to develop an alternate method of compliance that would permit credits for thermal mass and passive solar without going to a systems approach (New Mexico Energy Institute, 1981, and Robertson, 1981). Recognizing that steady-state R-values quantify *peak* wall and window losses or gains, research conducted through the New Mexico Energy Institute at the University of New Mexico calculated effective U-values, which quantify *average* heat flows. By the time 90-75 was implemented in late 1977, builders could simply replace steady-state values with effective U-values that varied with wall type, climate region, color, and orientation. For example, a 10-in. (25-cm) uninsulated, dark-colored, south-facing adobe wall, which has a steady-state U-value of 0.24 Btu/h ft^2 °F (1.4 W/m^2 K) (this includes interior and exterior finish and surface film coefficients), has an effective U-value of 0.05 Btu/h ft^2 °F (0.28 W/m^2 K) in the warmest climate, a reduction of 80%. The same wall in the coldest climate still shows a significant reduction to 0.13 Btu/h ft^2 °F (0.74 W/m^2 K). Similar calculations were performed for windows. For example, window areas that face south have a negative effective U-value, which indicates that they are net heat gainers.

Some years later, in 1982, California developed its own energy code, which includes thermal mass credits (Berkeley Solar Group, undated). For the component compliance method, mass is traded for R-value; that is, buildings with thermal mass in exterior walls require less R-value than those without thermal mass. In all climate zones and in all packages, walls with greater than 40 lbm/ft^2 (195 kg/m^2) of wall area require far lower steady-state R-values to meet the total building energy budget than buildings with lightweight walls. Typical R-value reductions are from R-19 and R-11 (RSI-3.4 and RSI-1.9) to R-2.5 (RSI-0.4). Note, however, that California has relatively mild climates--the coldest climate has only about 5600°F day (3100°C day) heating degree-days. Such large reductions in insulation levels would not be recommended in New Mexico.

Note that both of these energy codes state performance in terms of *wall* performance, whereas the SWTMS and other thermal mass research results discussed earlier generally state performance in terms of whole building performance. This explains why the thermal mass effects in the codes seem to be much greater. Even after taking this into account, significant disagreement still exists among the research results. This is to be expected; the results are not likely to be the same because of varying computer models, assumptions, climates, and building configurations.

According to Howard, as of 1985, credits for thermal mass are part of the energy code for the following ten states: Arizona, California, Colorado, Florida, Nevada, New Mexico, North Carolina, Oregon, Utah, and Washington. These include many of the states where adobe is used. Results are now being compared and refined, and simple, accurate predictive methodologies are being developed. It will likely be several more years before thermal mass credits are used on a nationwide basis.

RECOMMENDATIONS ON USE OF THERMAL MASS

This section presents specific recommendations on how best to utilize adobe or other thermal mass materials in an energy-efficient manner. Some recommendations are specific to New Mexico and the southwestern United States, but the theory, and the recommendations in general, are applicable anywhere in the United States. The recommendations are based on the Southwest Thermal Mass Study results, current thermal mass research, and current knowledge about passive solar systems. Many of the recommendations are summarized in Figures 6 and 7.

Concepts

It pays to take advantage of the unique properties of thermal mass discussed earlier. The ability of mass to store heating or cooling energy, as in passive solar applications, produces the greatest "mass effect" and saves the most energy. Passive solar techniques will perform well in massive structures in all but the mildest heating climates. Use the moderation of heat flow to reduce energy use and provide a comfortable and steady radiative environment. Use the delay to reduce peak heating and cooling loads and shift loads to off-

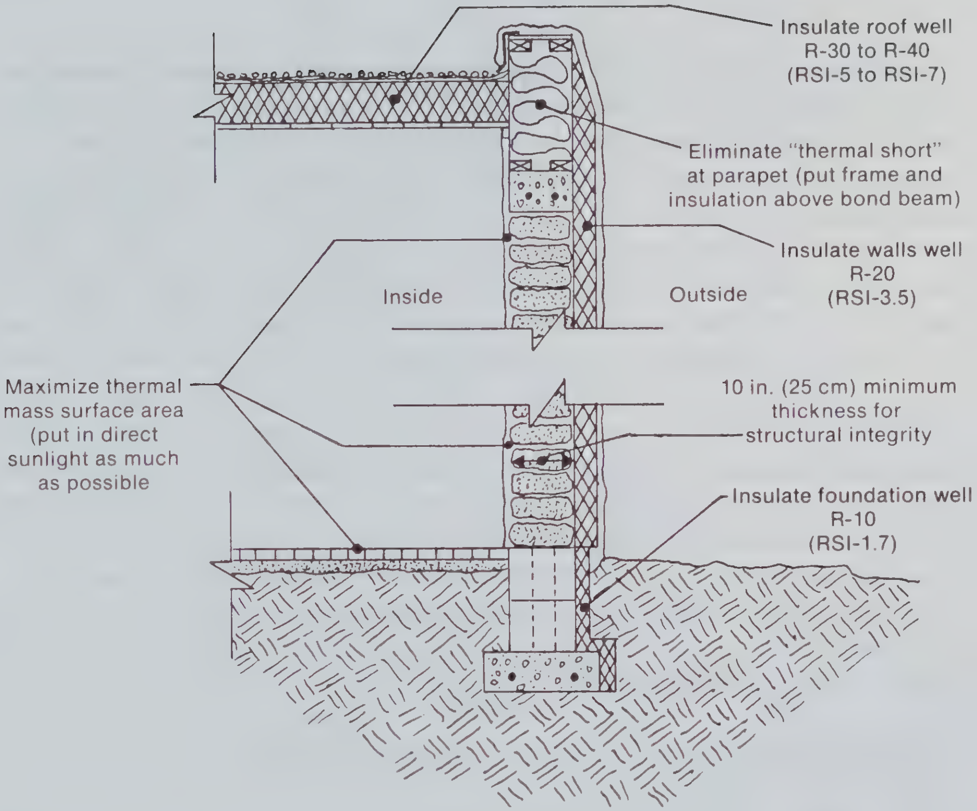


Figure 6. **Recommendations for use of thermal mass in east, west, and north walls**

peak hours when you can use natural heating or cooling sources. Reducing peak loads also reduces the capacity and hence the cost of heating and cooling equipment.

Density

The denser (and usually more conductive) a mass material is, the better, particularly for passive solar applications. This is the exact opposite of wanting a high R-value (low density) for adobe. Mass and insulation have separate functions but can be designed to work together harmoniously. The object is to get as much heat as possible into and out of the mass on a daily basis.

Thickness

A thickness of 10 in. (25 cm) of adobe seems to be optimum for most applications. The main reason for this is that it provides the

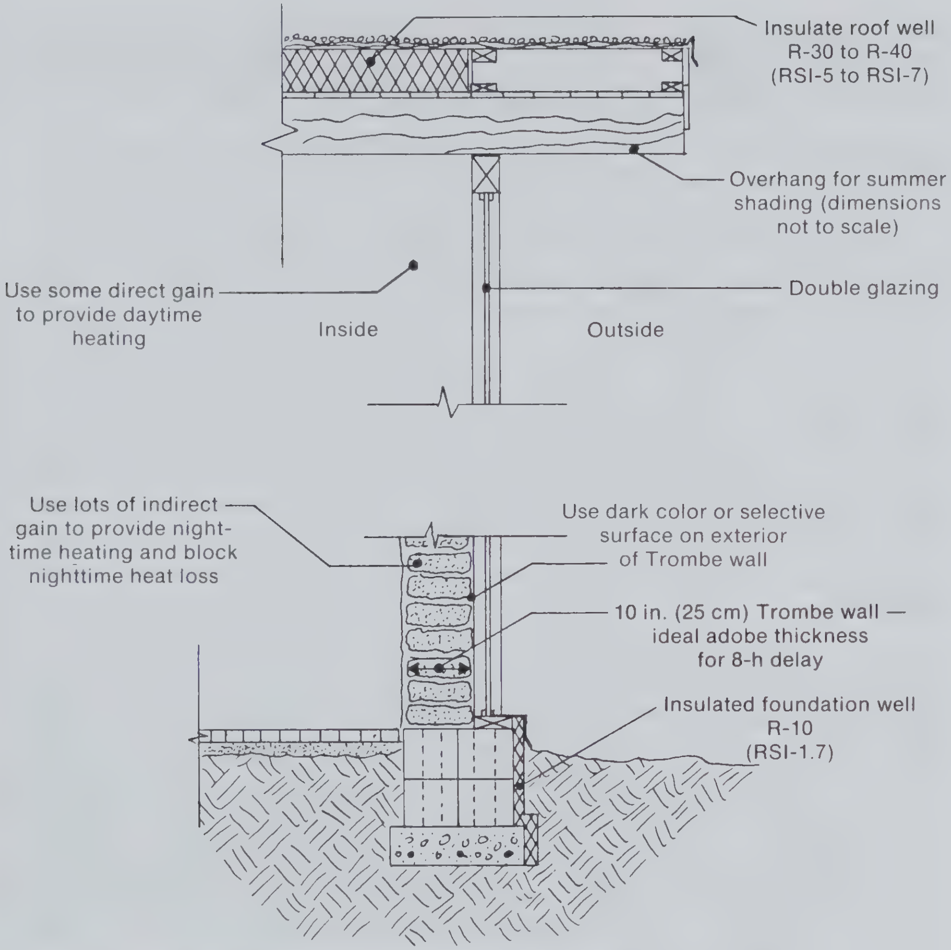

Insulate roof well
R-30 to R-40
(RSI-5 to RSI-7)
Overhang for summer shading (dimensions not to scale)
Use some direct gain to provide daytime heating
Inside
Outside
Double glazing
Use lots of indirect gain to provide nighttime heating and block nighttime heat loss
Use dark color or selective surface on exterior of Trombe wall
10 in. (25 cm) Trombe wall — ideal adobe thickness for 8-h delay
Insulated foundation well
R-10
(RSI-1.7)

Figure 7. Recommendations for use of thermal mass in south walls

optimum delay, whether for heat flow through conventional exterior walls or through passive solar Trombe walls. A 10-in. (25-cm) wall provides about an 8-h delay, which is good for both heating and cooling. Note, however, that for well-insulated adobe walls, the daily variation in heat flow is quite small, so that only a small peak is shifted.

For interior solar storage, as with direct gain, solar research at Los Alamos indicates that only the first 2-4 in. (5-10 cm) of most mass materials is usable for heat absorption, storage, and release on a daily basis. Although 4-in. (10-cm) adobe interior veneer could be used, 10 in. (25 cm) will provide thermal storage for periods longer than a day, and it will provide building structural requirements as well. Interior partition walls of 10-in. (25-cm) adobe will be particularly effective because both sides will provide thermal storage.

Surface Area

In direct-gain applications, surface area is usually the most important parameter of thermal mass. For both conventional and solar applications, maximize the amount of mass that is in direct contact with the room air and that is in direct visual (radiant) contact with the occupants. Place as much mass area as possible in direct sunlight; radiative coupling is far more effective than convective coupling and will reduce overheating. In terms of direct gain thermal performance, there is no "ideal" amount of thermal mass or thermal mass surface area--the more, the better.

Insulation

Insulate thermal mass walls as you would any other exterior walls. Insulation is recommended in all climate zones of New Mexico. Suggested levels for much of New Mexico are: roof, R-30 to R-40 (RSI-5 to RSI-7); walls, R-20 (RSI-3.5) (in addition to the R-value of the mass); stem walls (for on-grade floors), R-10 (RSI-1.7). Use more insulation in very cold zones or when heating with electricity. In hot zones in New Mexico, you could use less insulation because evaporative cooling is so energy-efficient, but not if you use mechanical air conditioning.

An important finding of the SWTMS and the NBS study (Burch et al., 1983), was that floor losses for slab-on-grade floors are significant. Insulating *under* on-grade floors is not usually necessary, or even desirable, but it is important to insulate the stem walls. Be sure to insulate any other potential "thermal shorts" in the building envelope, such as parapets (Figure 6).

Always insulate the *exterior* of thermal mass; again, thermal contact with the interior space is the key. As a general rule, insulate on the north, east, and west, and glaze the south. The north can take a little more insulation than east and west. Any unglazed south wall area should also be insulated.

Insulate walls with rigid insulation. Three inches (7.6 cm) of polyurethane or polyisocyanurate will provide R-21 (RSI-3.7), and the cost per R is only marginally greater than polystyrene. Two other methods are used. Foam-in-place polyurethane is more expensive than the rigid form, but it seals the building well, and it may be more aesthetically pleasing than the flat surfaces of the rigid insulation. A third option is a frame/batt curtain wall attached to the exterior of the adobe. This also is more expensive than the rigid insulation.

Air Infiltration

Because adobe is a continuous, sealed material, air infiltration is usually (but not always) less than in other types of construction. Current construction practice includes exterior stucco and interior plaster, which protect against infiltration through any cracks or gaps that may exist or develop in the adobe wall. Furthermore, there is no indirect infiltration, as can occur in frame walls, where air can penetrate the exterior finish and into the framing/insulation cavity (thereby reducing the effectiveness of the insulation), but not necessarily into the heated space. In general, massive structures are less susceptible to any air infiltration that is present because the heat is stored in the mass, not in the air. In any building, massive or not, air infiltration is commonly a major source of heat loss, and careful attention should be paid to caulking and weatherstripping.

Ventilation

In the heating season, ventilation should be used sparingly to remove odors, excessive moisture, unacceptable or toxic fumes, or radon gas. Homes that are very tightly constructed should use ventilation more. Ventilate during the day, when outside air temperatures are warmer. In very tight buildings, indoor air quality can be affected. In such cases mechanical ventilation may be needed in which an air-to-air heat exchanger recovers heat from the outgoing air.

In the cooling season when the cooling system is on, leave windows open for evaporative cooling. If you live in a humid area that requires mechanical air conditioning, keep windows closed.

When the cooling system is not on, thermal mass can be used to its full advantage. When outside air temperature drops to a comfortable level, open windows and doors for natural ventilation. Since 10-in. (25-cm) adobe has an 8-h delay, often this will be when the peak heat pulse is coming through the walls, although in a well-insulated adobe wall, the peak will not be much greater than the average. Ventilate all night and in the early morning until outside air temperature rises to an uncomfortable level. Then close all windows and doors; the mass is cool because of nighttime rejection of heat and will keep the space comfortable. Such a strategy can delay the use of the cooling system well into the cooling season, or prevent its use entirely, depending on the climate.

Thermostat Setback

An important strategy for saving energy in lightweight buildings is thermostat setback (or "set-up" in the cooling season) during periods when the building is not in use, or when lower (or higher) temperatures can be tolerated, such as at night. Although this strategy is less effective in massive structures because they take longer to cool down and heat up, it still may be effective. Remember that the building will take longer to respond, so the thermostat setback should be smaller, and the time of the reset to normal should be earlier, than in lightweight buildings.

Comfort

Human comfort is a complex phenomenon that involves numerous factors, including air temperature, air velocity, relative humidity level, the radiant environment (surface temperature and location), clothing and activity level, and acclimation. The key factors are air temperature and the radiant environment temperatures. If the surfaces that the human body "sees" and radiates to are at a temperature below the comfort region, say 55°F (13°C), air temperature will need to be greater than normal comfort temperatures, perhaps 80° or 85°F (27° or 29°C). [Note that a thermostat also responds somewhat to the radiant environment, so a thermostat setting of 75°F (24°C) might produce an air temperature of 80° or 85°F (27° or 29°C).] This is the case in an uninsulated adobe in midwinter. Similarly, if the radiant environment is warm, lower air temperatures can be tolerated to provide the same comfort level. This is often the case in a passive solar house.

Massive walls reduce variation in the radiant environment and contribute to a more steady overall thermal environment. If walls are at temperatures within the comfort range, this increases comfort, particularly during transition seasons (spring and fall), during dramatic air temperature changes (high solar gain or door open), and in climates that have high daily temperature swings such as New Mexico. Any changes in air temperature that do occur will be slower than in lightweight buildings.

Other Massive Materials

These recommendations and discussions apply to all other types of earthen construction, as well as to other high-density massive materials such as concrete, bricks, or blocks. In general, the denser and more conductive the material is, the better it performs, particularly as a passive solar heat storage medium. Materials with different thermal properties will likely have different time delay properties, so adjust thicknesses to get the desired delay.

ACKNOWLEDGMENTS

I would like to thank the following individuals and organizations for their participation in the development of this article: the New Mexico Research and Development Institute, the U.S. Department of Energy, and other funding agencies; Bill Haney, who conceived and developed the Southwest Thermal Mass Study (SWTMS); John Gustinis, previous technical director of the SWTMS, and other researchers in the field; members of the adobe industry; and the reviewers of the article, including John Gustinis, Jeff Christian, and P.G. McHenry.

REFERENCES

Adobe News, Inc., 1985. *Adobe Codes from Around the Southwest—A Guide to the Codes of Arizona, California, Texas, and New Mexico.* Albuquerque, NM: Adobe News, Inc.

Arumi, F.N., 1977. *Thermal Inertia in Architectural Walls.* McLean, VA: National Concrete Masonry Association.

ASHRAE (American Society of Heating, Refrigerating and Air-Conditioning Engineers), 1975 and 1980. *Standard 90, Energy Conservation in New Building Design.* Atlanta, GA: ASHRAE.

ASHRAE, 1985. Standard 90--The process, background, and the planning. *ASHRAE Journal* (Oct.).

Balcomb, J.D., R.W. Jones, R.D. McFarland, and W.O. Wray, 1984. *Passive Solar Heating Analysis.* Atlanta, GA: ASHRAE.

Berkeley Solar Group, undated. *Credit for Massive Exterior Walls in the Residential Energy Code of the State of California.* Sacramento, CA: Concrete Masonry Association of California and Nevada.

Burch, D.M., W.E. Remmert, D.S. Krintz, and C.S. Barnes, 1983. A field study of the effect of wall mass on the heating and cooling loads of residential buildings. *Proc. Building Thermal Mass Seminar—1982* (Knoxsville, TN, May 1982). CONF-8206130. Oak Ridge, TN: Oak Ridge National Laboratory.

Byrne, S.J., and R.L. Ritschard, 1986. Thermal mass in exterior walls of residential buildings. *Concrete Masonry Solar Architecture* 6(1):1-5. Herndon, VA: National Concrete Masonry Association.

Carroll, W.L., R. Sullivan, and A. Mertol, 1985. *Thermal Mass: BLAST Residential Parametric Simulations.* Draft LBL-19681. Berkeley, CA: Lawrence Berkeley Laboratory.

Catani, M.J., 1978. Insulation and the 'M' factor. *ASHRAE Journal* (June).

Childs, K.W., 1983. *Thermal Mass Assessment—An Explanation of the Mechanisms by Which Building Mass Influences Heating and Cooling Energy Requirements.* ORNL/CON-97. Oak Ridge, TN: Oak Ridge National Laboratory.

Christian, J., 1985. A statistically based parametric analysis of exterior envelope thermal mass effect predictions. *Proc. ASHRAE/DOE Thermal Performance of the Exterior Envelopes of Buildings Conf.* (Clearwater, FL, Dec. 1985). Washington, DC: U.S. Department of Energy.

Gustinis, J.P., and D.K. Robertson, 1981. *Southwest Thermal Mass Study—Construction and Instrumentation Phase.* NMRDI 2-67-1135(a). Albuquerque, NM: New Mexico Research and Development Institute.

Gustinis, J.P., and D.K. Robertson, 1984. *Southwest Thermal Mass Study—Research Phase I: The Effect of Envelope Thermal Mass on the Heating Energy Use of Eight Test Buildings in a High Desert Climate.* NMRDI 2-67-1135(I). Albuquerque, NM: New Mexico Research and Development Institute.

Howard, B.D., 1984. Performance portrait of high-mass houses. *Solar Age* (Sept.).

Howard, B.D., 1985. Masonry thermal mass and the energy codes. *The Construction Specifier* (June).

HUD, 1985. Minimum property standards for one and two family dwellings; final rule. *Federal Register* 50(188), 24 CFR Part 200 (Sept. 27, 1985). Washington, DC: U.S. Department of Housing and Urban Development.

McHenry, P.G., 1984. *Adobe and Rammed Earth Buildings: Design and Construction.* New York: John Wiley and Sons.

New Mexico Energy Institute, 1981. *Energy Conservation Code Applications Manual.* Albuquerque, NM: New Mexico Research and Development Institute.

Robertson, D.K., 1981. *Expanded Revision of Effective U-Values.* NMRDI 2-68-1111. Albuquerque, NM: New Mexico Research and Development Institute.

Robertson, D.K., 1984. *Southwest Thermal Mass Study—Research Phase II: Observation and Prediction of the Heating Season Thermal Mass Effect for Eight Test Buildings With and Without Windows.* NMRDI 2-67-1135(II). Albuquerque, NM: New Mexico Research and Development Institute.

Steven Winter Associates, 1983 and 1985. *Affordable Housing Through Energy Conservation* (including Masonry Update, 1985). DOE/CS/20524-6 (Draft). Washington, DC: U.S. DOE.

Passive Solar Journal, 3(4), 419-433 (1986)

A Passive Florida House

Herb Beatty
Solar Energy Associates
9509 My Way Lane SW
Fort Myers, Florida 33907

Abstract

This paper describes the design, construction details, and first year performance of a passive solar home recently built in southwest Florida. The objective was to achieve maximum comfort with minimum energy use by combining proven passive solar cooling techniques with the latest state-of-the-art passive cooling developments such as radiant barriers and vent skin walls and roof.

The home is designed around a three-level central core area that induces a "stack effect" to create an artificial breeze throughout the house for summer cooling. A galvanized metal roof with a 4-ft (1.2-m) overhang provides shading for walls and windows and incorporates a *vent skin and radiant barrier system. The east and west walls, mostly unprotected by the roof overhang, contain a vent skin design along with the radiant barrier system.*

I have occupied the house for over 18 months, and during the first full year of operation this all-electric home used only 3379 kWh of electricity—less than one third the amount used by a comparable home in this area. Although completely open to the warm Florida climate, the house is remarkably cool without the use of air conditioners.

INTRODUCTION

The inspiration for the design and construction of this house originated at a 1976 National Association of Homebuilders conference. Motivated by a U.S. Department of Housing and Urban Development (HUD) presentation to compete in a solar home demonstration, I subsequently won two HUD awards. More recently, in 1984 I used the latest state-of-the-art information on low energy building design garnered from the Florida Solar Energy Center (FSEC) to design a house in Florida that would work with nature, not against it.

Studies and practice have shown how micro-climate affects the successful operation of a passive solar home. In response to the local environment, the passive systems incorporated in this home can be adjusted for daily and seasonal variations in temperatures, sun angles, and wind speed and direction to maximize comfort conditions. The involvement of the occupants is important in this design, primarily to adjust ventilation levels throughout the year.

CLIMATE

This house is located in Fort Myers, Florida, on the warm humid southwest gulf coast where cooling needs predominate. Average annual cooling degree-days are 4000°F day (2200°C day) while heating degree-days are only 380°F day (210°C day). Humidity averages 76% relative humidity during the summer months.

The prevailing wind from April through September is from the east and southeast at 5-9 mph (8-14 km/h). Afternoon breezes blowing in from the gulf typically are 10-12 mph (16-19 km/h) over the coastal areas.

Some heating is required from late November to mid-February. Solar radiation is a potential source for much of the heat needed. Cooling is required from May through September. Natural ventilation can satisfy this cooling requirement all day long during May and September, and in the early morning and late afternoon for the remaining summer months.

DESIGN CONCEPTS

For this project I chose a piling design or "stilt house" for several reasons. First, the raised living area allows for much improved ventilation, even achieving a modest "chimney effect" with the cooler air entering at the ground level utility room and naturally exhausting via stairways and louvers up into and out of the third floor loft room, without the aid of mechanical fans. Also, at 12-ft (3.7-m) elevation, the average wind velocity is measurably greater than at ground level. With this enhanced air movement one feels comfortable at significantly higher temperatures, further reducing the need for air conditioning. Figure 1 is a photograph of the house, and Figure 2 shows the site plan and prevailing winds.

The house is designed around a central core area that consists of a laundry/storage room at ground level with a kitchen on the second level and a loft space on the third level (Figure 3). These three interconnected layers act as a funnel to direct warm air up and out of the house through vents and operable windows located in the loft. Cooler replacement air from outside enters the core area through adjustable louvers and awning windows. By introducing this fresh air, the peripheral rooms are ventilated and at the same time fresh air is being introduced into the core area. Airflow patterns as confirmed by measurements with plastic streamers are shown in Figure 4.

Raising the main living areas off the ground reduces the insect problem as many of the pesky little critters don't fly this high. The added advantages of a better view and increased privacy are a bonus. In many coastal flood plain zones elevated living areas are mandated by law.

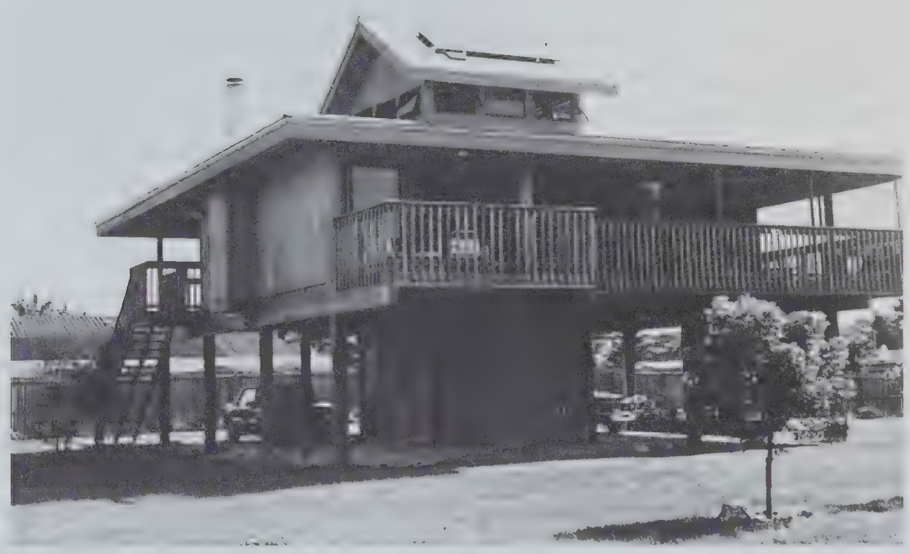


Figure 1. Passive solar house, Fort Myers, Florida

The main living areas face south. The large screened porch faces southeast, the same direction as the prevailing summer breeze in this locale. The sleeping areas are on the east and north, away from the late afternoon sun. Storage closet areas are on the east and west walls and serve as privacy buffers between rooms (Figure 3). Figures 5 through 8 show the elevations.

I placed the major glass areas on the south: two 8-ft (2.4-m) sliding glass doors that pocket back to allow a full 16-ft (4.9-m) opening for ventilation. I used a minimum of windows on east and west walls, none in the main living area. The necessary east and west windows are protected from direct sun with reflective foil. Louvered Bahama shutters were a consideration, but so far have proved to be unnecessary. A 4-ft (1.2-m) overhang all around the house does not protect the east and west windows or the walls from the low morning or afternoon sun, so there I used a vent skin wall design. The overhang does adequately protect the large glass areas facing south; no sun strikes them from April 15 to October 15. Lower winter sun is admitted to provide passive heating during our moderate winter cool spells.

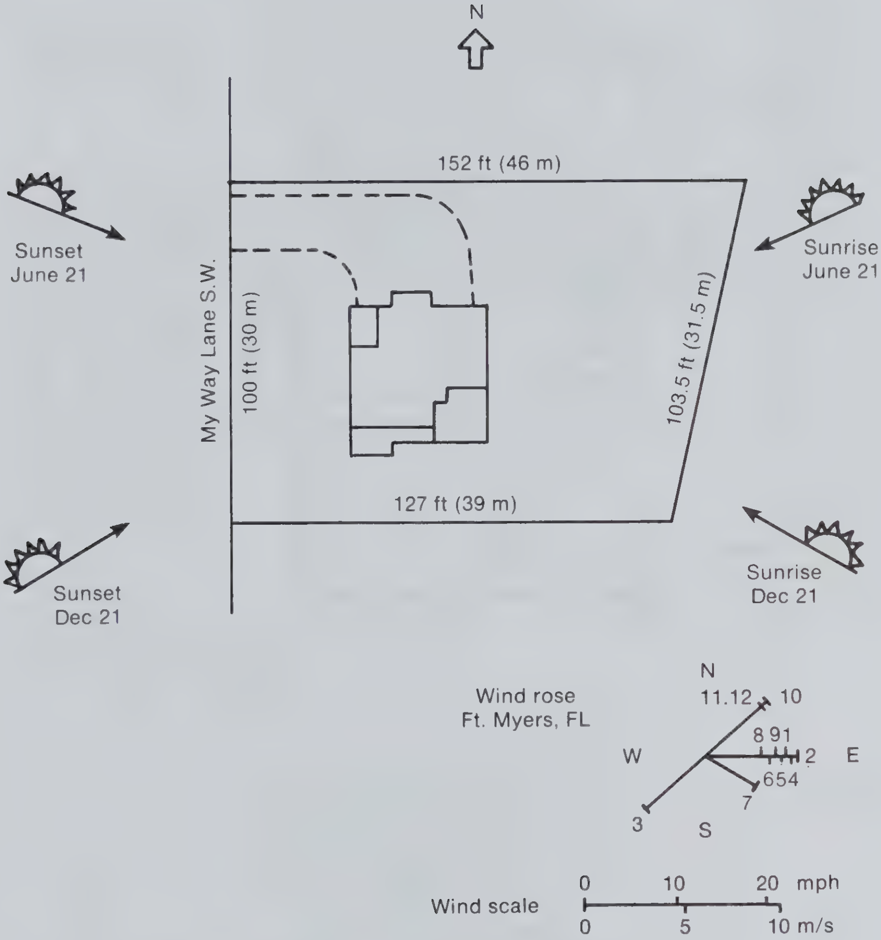


Figure 2. Site plan with sun angles and prevailing winds

Because most of the summer heat gain in a typical Florida house enters through the roof, I used galvanized metal roofing to reflect some of the intense solar radiation plus an aluminum radiant barrier built into the roof structure (Figure 9). The radiant barrier consists of a thin sheet of aluminum foil deposited on a reinforced substrate and applied shiny side down on top of the roof rafters before the 0.5-in. (1.3-cm) plywood roof sheathing is laid down. The foil is drooped down about 2 in. (5 cm) between rafters to allow an air space above the foil. The space also provides a path for air up and out through the ridge vent. This radiant barrier system reflects 95% of the radiant heat striking the roof and prevents the high heat build-up in the roof structure and R-19 (RSI-3.4) fiberglass roof insulation that would otherwise occur. This combination of radiant

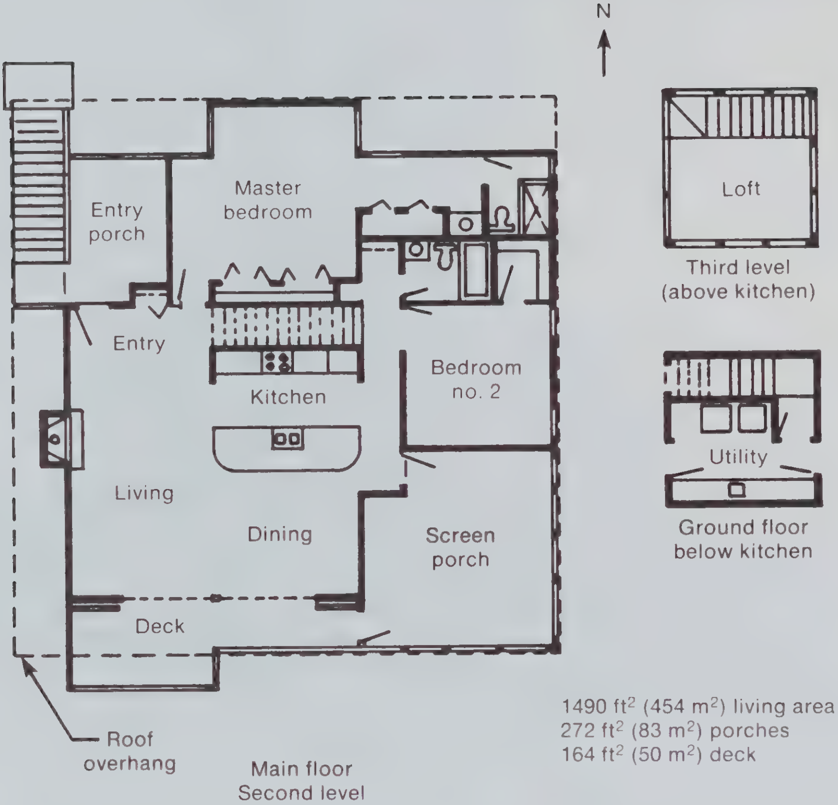


Figure 3. Main, loft, and utility floor plans

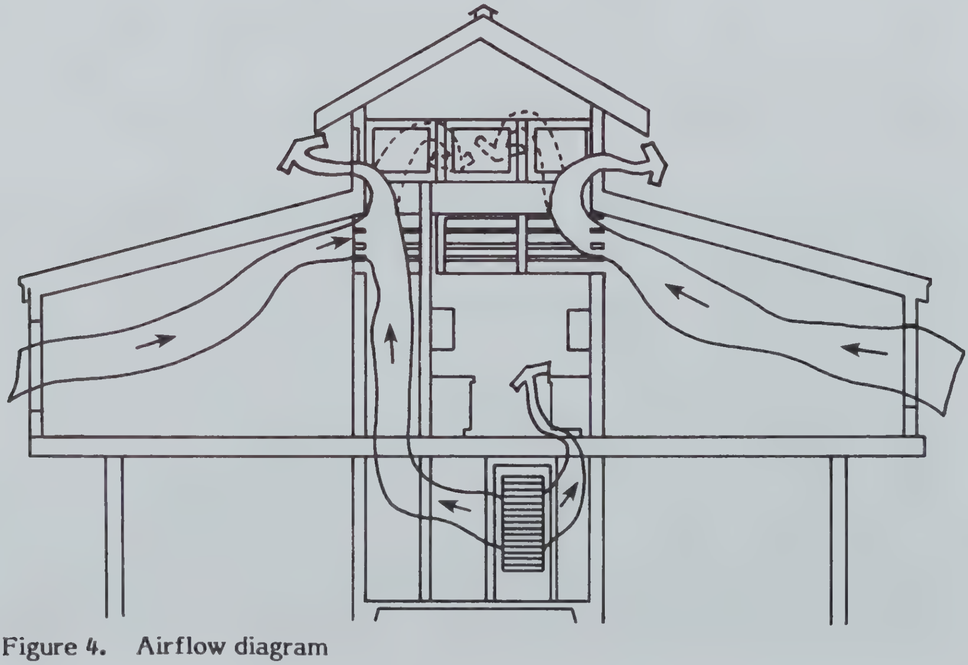


Figure 4. Airflow diagram

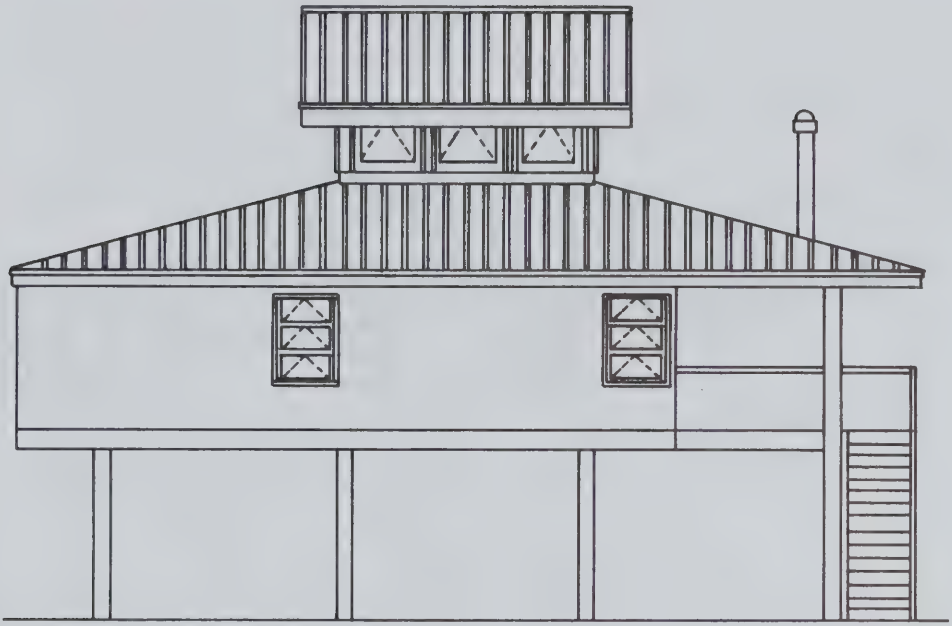


Figure 5. North elevation

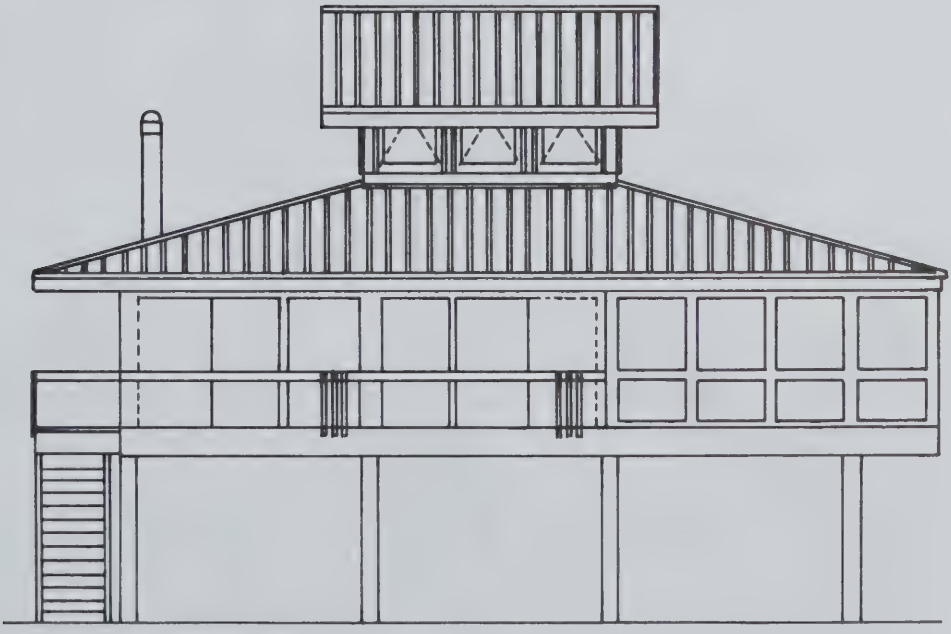


Figure 6. South elevation

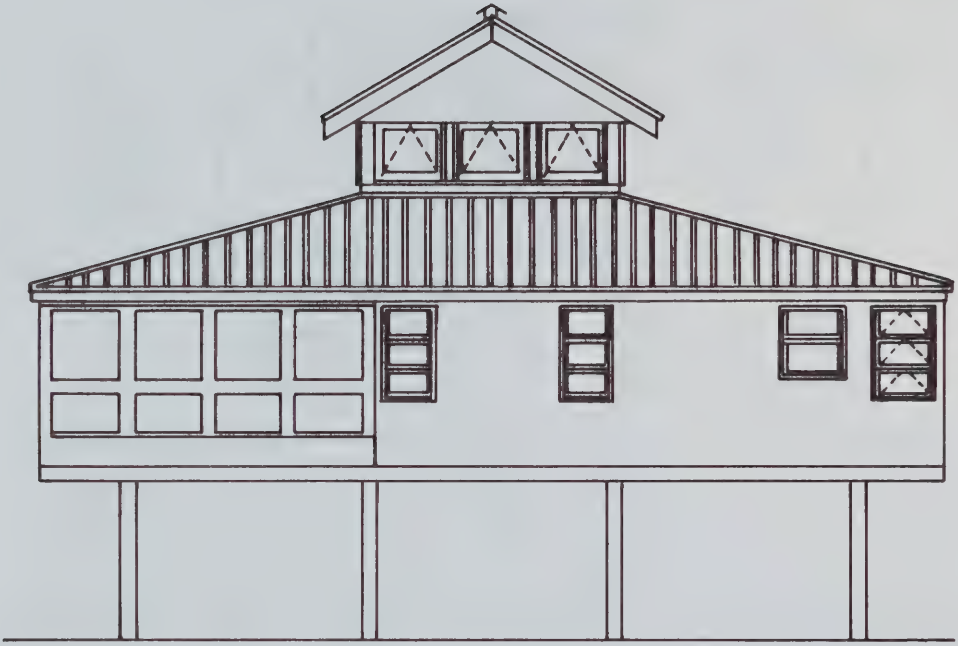


Figure 7. East elevation

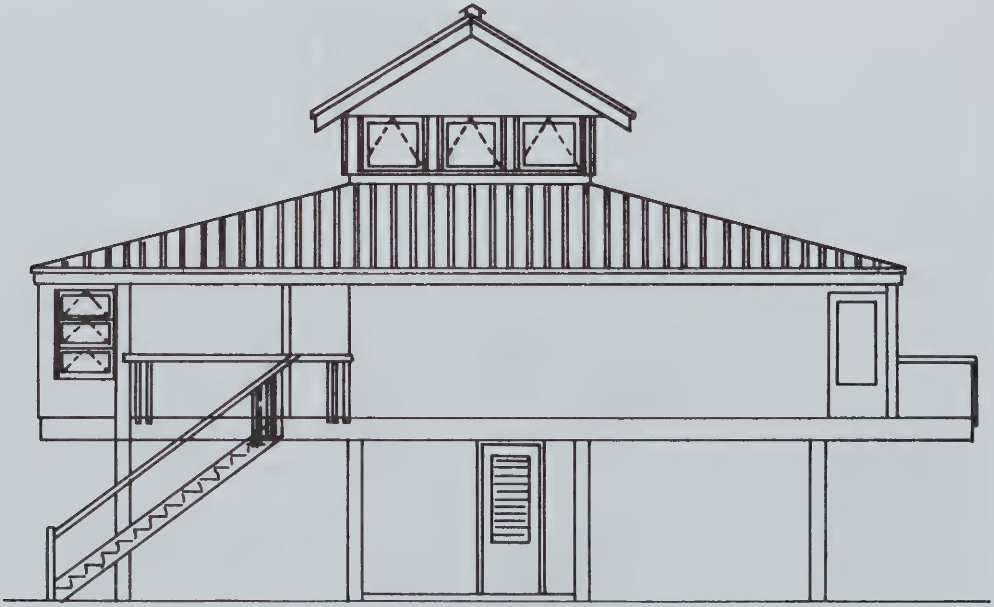


Figure 8. West elevation

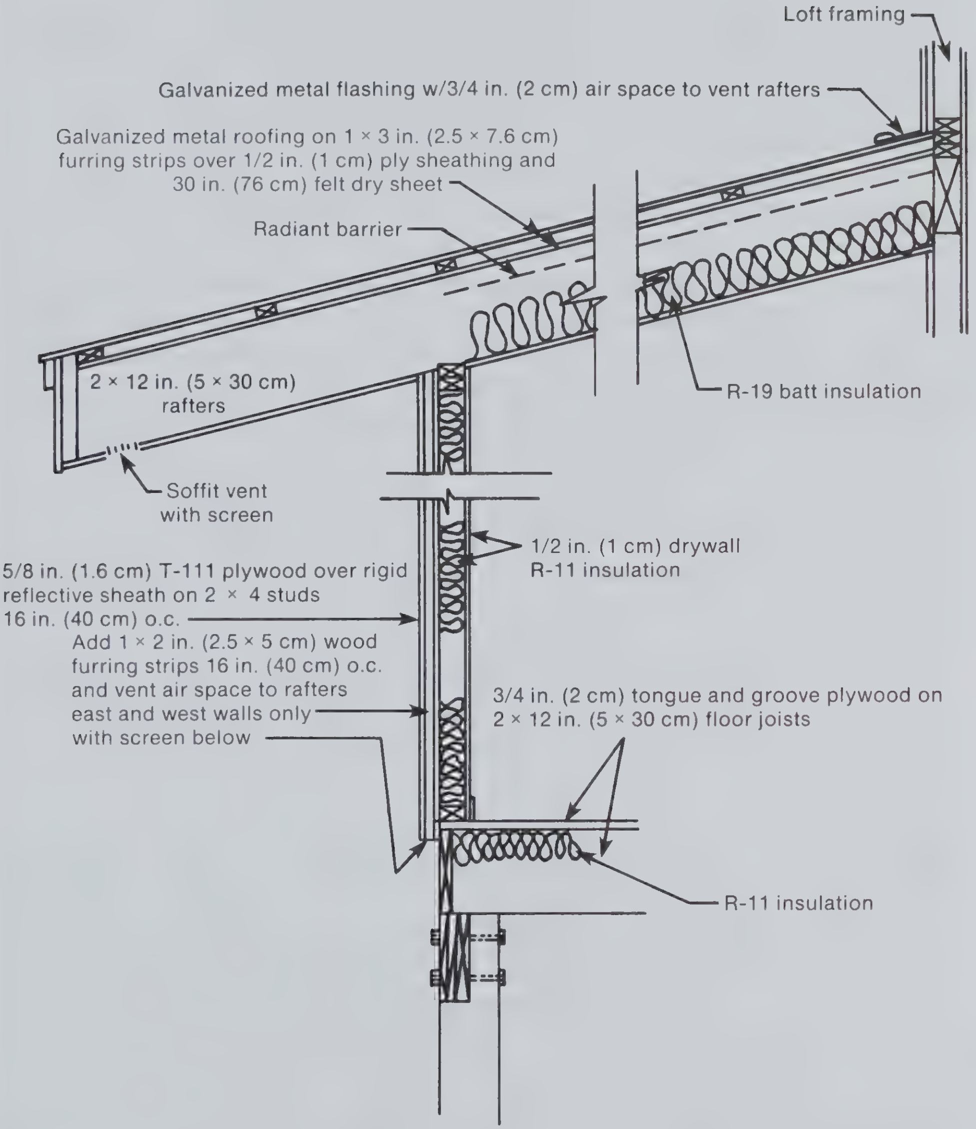

Loft framing
Galvanized metal flashing w/3/4 in. (2 cm) air space to vent rafters
Galvanized metal roofing on 1 × 3 in. (2.5 × 7.6 cm) furring strips over 1/2 in. (1 cm) ply sheathing and 30 in. (76 cm) felt dry sheet
Radiant barrier
2 × 12 in. (5 × 30 cm) rafters
R-19 batt insulation
Soffit vent with screen
1/2 in. (1 cm) drywall
R-11 insulation
5/8 in. (1.6 cm) T-111 plywood over rigid reflective sheath on 2 × 4 studs 16 in. (40 cm) o.c.
Add 1 × 2 in. (2.5 × 5 cm) wood furring strips 16 in. (40 cm) o.c. and vent air space to rafters east and west walls only with screen below
3/4 in. (2 cm) tongue and groove plywood on 2 × 12 in. (5 × 30 cm) floor joists
R-11 insulation

Figure 9. Wall and roof sections

barrier and R-19 (RSI-3.4) batt insulation is more effective than an R-48 (RSI-8.5) batt in reducing heat gain - and much less costly to install.*

---

*R in unit h ft^2 °F/Btu, RSI in m^2 K/W.

While the radiant barrier does reduce winter heat gain through the roof, it also helps retain the heat inside, which results in a net heat gain in winter. FSEC experiments have shown the radiant barrier to be cost effective in reducing summer heat gain as far north as Baltimore. Essential to the proper functioning of a radiant barrier is the presence of the reflective metallic (low-emittance) surface and an air space on at least one side.

The aluminum foil is draped over the rafters with the shiny side facing down. The radiant barrier will function equally well facing up or down, but eventual dust accumulation on an upward-facing shiny surface would degrade the performance. The 1986 Florida Energy Efficiency Code details this preferred installation procedure.

To further cut down on heat gain, I used a vent skin construction on the east and west walls of the home, which provides for a 3/4-in. (1.9-cm) screened air space between the T-111 exterior siding and the radiant barrier sheathing (Figure 9). The air space allows the radiant barrier to function. It also provides a series of "wall chimneys" that let the air within the space rise and carry away the heat generated by low sun angles shining directly on the siding. This air travels up and out through the roof ventilation system.

The home is also equipped with a 4 × 10 ft (1.2 × 3.1 m) flat-plate panel solar hot water system that provides all my hot water requirements. The hot water storage tank is in the ground floor level utility area where a photovoltaic-powered pump lifts the water up to the solar panel atop the south loft roof. This pump system operates automatically whenever sufficient sunlight activates the photovoltaic cells that drive the pump. Thus the domestic hot water system is totally solar-powered.

MECHANICAL COOLING

The house is equipped with a Carrier 3.5 hp high efficiency (SEER 9.5) conventional air-conditioning system. Frequently, when the humidity or temperature is high and there is little or no breeze, we use the air conditioner. However, the heat-gain-avoidance technique incorporated in the house greatly reduces the load. Also, adjustable-speed ceiling fans in all major rooms maintain comfort and further reduce the load.

A metal heat circulating fireplace supplies much of the needed heat in the winter. A backup electric strip heater is installed in the air conditioning ductwork, but is rarely used.

CONSTRUCTION DETAILS

The wood piling foundation is composed of 8-in. (20-cm) pine timbers with a 30-yr "Wolmanized" special salt water intrusion treatment. The timbers are dug in by hand to a depth of 6 ft (1.8 m). To insure stability of the central core, the pilings supporting the three-level section were set in 4 × 1.5 ft (122 × 46 cm) concrete feet with a 3/4-in. (2-cm) Rebar inserted 8 in. (20 cm) up from the bottom of the piling into the concrete. In this hurricane-prone area, the piling foundations for stilt homes must be designed to withstand the much greater force of the upward thrust that a hurricane-force wind would impart. On the barrier islands just off the coast the new code requirement calls for structures to withstand 140 mph (225 km/h) winds--a comforting thought!

The entire substructure of the house is framed with 2 × 12 in. (5 × 30 cm) pressure-treated southern yellow pine. The three beams running from piling to piling are 2 × 12 in. (5 × 30 cm) fastened every 4 ft (120 cm) with two 3/4-in. (2-cm) galvanized bolts and are also bolted into the notched piling tops. The floor joists are 24 in. (61 cm) o.c. and fastened securely with galvanized hurricane straps. The subfloor is 3/4-in. (2-cm) tongue-and-groove Waferwood, a very strong--by its density--and waterproof wood fiber product, which is an improvement over laminated plywood previously used in this region.

Wall framing is conventional 2 × 4 in. (5 × 10 cm) with all window and door headers being double 2 × 10 in. (5 × 25 cm). Outside, the wall framing is a Thermoply Storm Brace reflective sheathing with R-11 (RSI-1.9) fiberglass insulation between the 2 × 4 in. (5 × 10 cm) studs.

On the west and east walls the vent skin detail is achieved in three steps: by installing radiant barrier material directly on the outside of the sheathing, shiny side facing out; by applying 1 × 2 in. (2.5 × 5 cm) strips vertically on top of the radiant barrier and exactly opposite each wall stud to provide adequate nailing; and by installing the exterior siding over the 1 × 2 in. (2.5 × 5 cm) strips, after which an aluminum soffit vent type screening is placed at the bottom of the wall to serve as an insect/bird screen.

The structural shell of the house is ventilated by a combination of continuous soffit vents at the outer edge of the overhang and continuous ridge vents. The ridge vents are at the peak of the gable roof above the upper loft area. Also, on all four sides of the loft structure, there are vent spaces under 8-in. (20-cm) deep flashing where the main level roof meets the outside of the loft. This allows the main roof to release air from the vent skin walls and also from the roof space. Research by FSEC has determined that the radiant barrier system is significantly more effective in combination with proper soffit and ridge venting. These attempts to apply some old and new passive solar cooling strategies to an actual house have been very rewarding, both in the comfortable living environment the house provides and in the outstanding energy savings already demonstrated.

Construction began on September 4, 1984, and I moved in on November 1, 1984. Since then this house has been continuously occupied by one to three adults.

OPERATION

After two months of occupancy my home was featured in a local solar home tour in January 1985. Approximately 400 visitors liked the open plan, the view, the abundance of daylight, and the general arrangement. The passive solar heating was very evident in January. However, the warm weather performance was and is the proof of the design. Visitors are astonished at the cool comfort of the home although it is completely open to the warm Florida climate. People inspecting the house are interested in seeing the lightweight plastic streamers attached to louvers and windows indicating the airflow, and in checking the thermometers that show temperatures at various inside and outside locations.

The house uses electric power only supplying oven/range, frostfree refrigerator, dishwasher, microwave oven, clothes washer and dryer, stereo, five ceiling fans - even an electric barbecue, plus a 3.5 ton "Carrier" air conditioning system (SEER 9.5). For the 8-month period March through October 1985 a total of 1689 kWh of electricity were used, an average of 211 kWh per month. At the local rate, the average monthly electric bill was $21.85. The air-conditioning system was available but rarely used - typically on occasional hot, humid, and breezeless days. The average electric bill for such a period in a conventional house of comparable size would be about $125 a month (Tables 1 and 2).

This house was designed and built to demonstrate the benefits of using the best of existing technology in creating a comfortable, livable home that works with nature, not against it. The principles involved are applicable to residential and small commercial buildings throughout the sun belt. I hope that the use of these simple but effective strategies will become widespread soon.

Table 1a. Monthly Weather Data for Ft. Myers, Florida (English Units)

	Dry Bulb Temp., °F Max.	Min.	Ave.	Average Relative Humidity, %	Degree Days, °F day Heating[a]	Cooling[b]	Average Wind Speed and Direction, mph	
Jan	74.3	62.6	68.0	75	141	0	8	E
Feb	75.1	64.6	69.4	71	89	0	9	E
Mar	77.1	64.0	69.7	68	37	0	10	SW
Apr	79.1	69.3	74.0	70	0	90	8	E
May	83.0	72.3	77.7	73	0	380	9	E
Jun	84.7	76.2	80.4	77	0	720	7	E
Jul	86.6	78.2	82.3	78	0	826	6	SE
Aug	88.1	78.3	82.6	74	0	825	5	E
Sep	88.8	77.2	81.7	77	0	700	7	E
Oct	81.4	72.5	78.6	77	0	380	8	NE
Nov	78.9	69.2	73.2	72	20	65	8	NE
Dec	75.6	62.8	68.7	71	90	0	8	NE

[a] Base 65°F
[b] Base 75°F

Table 1b. Monthly Weather Data for Ft. Myers, Florida (Metric Units)

	Dry Bulb Temp., °C Max.	Min.	Ave.	Average Relative Humidity, %	Degree Days, °C day Heating[a]	Cooling[b]	Average Wind Speed and Direction, km/h	
Jan	23.5	17.0	20.0	75	78	0	13	E
Feb	23.9	18.1	20.7	71	49	0	14	E
Mar	25.0	17.8	20.9	68	21	0	16	SW
Apr	26.2	20.7	23.3	70	0	50	13	E
May	28.3	22.4	25.4	73	0	211	14	E
Jun	29.3	24.5	26.9	77	0	400	11	E
Jul	30.3	25.7	27.9	78	0	459	10	SE
Aug	31.2	25.7	28.1	74	0	458	8	E
Sep	31.5	25.0	27.6	77	0	389	11	E
Oct	27.4	22.5	25.9	77	0	211	13	NE
Nov	26.0	20.7	22.9	72	11	36	13	NE
Dec	24.2	17.1	20.4	71	50	0	13	NE

[a] Base 18.3°C
[b] Base 23.9°C

Table 2. Monthly Total Cost of Electricity vs Actual Degree Days

		kWh Used	Cost, $	Degree Days °F day (°C day) Heating[a]		Cooling[b]	
1985							
	Mar	180	19.20	6	(3)	18	(10)
	Apr	204	21.39	7	(4)	99	(55)
	May	142	16.61	0	(0)	525	(292)
	Jun	163	18.22	0	(0)	828	(460)
	Jul	243	24.39	0	(0)	765	(425)
	Aug	442	39.75	0	(0)	900	(500)
	Sep	170	18.76	0	(0)	779	(433)
	Oct	145	16.48	0	(0)	723	(402)
	Nov	176	18.29	0	(0)	174	(97)
	Dec	371	33.35	124	(69)	0	(0)
1986							
	Jan	543	46.19	89	(49)	0	(0)
	Feb	600	50.44	30	(17)	0	(0)
	Mar	394	35.07	67	(37)	33	(18)
	Apr	192	19.16	0	(0)	39	(22)
	May	181	18.38	0	(0)	388	(216)
	Jun	251	22.07	0	(0)	739	(411)
	Jul	225	20.35	0	(0)	N/A	

[a] Base 65°F (18.3°C)
[b] Base 75°F (23.9°C)

Passive Solar Journal, 3(4), 435-438 (1986)

Book Review

Concepts and Practice of Architectural Daylighting

Fuller Moore. New York: Van Nostrand Reinhold Company. 1985.
290 pp. ISBN 0-442-26439-9. Hardbound. $39.95.

With *Concepts and Practice of Architectural Daylighting*, Fuller Moore has filled a gap in the daylighting library by writing a much-needed and long-awaited book. This "collection of concepts and design tools," as Moore describes his book, presents daylighting clearly enough that a practicing architect, unfamiliar with daylighting, can effectively incorporate it into his or her design. Daylighting is presented from both the conceptual (design) point-of-view and from the analytic (quantitative) point-of-view. *Concepts and Practice* is not "a poetic tribute to the joys of daylit buildings" nor a step-by-step methodology of quantifying daylight in a building. Instead, this book occupies a middle ground, addressing those who are already interested in designing daylit buildings and yet have little technical knowledge of the subject. In a very readable style enhanced by numerous illustrations, Moore presents daylighting to the practicing architect in the context of other building issues such as structural systems, materials, and energy use.

Concepts and Practice is organized such that it can be used both as an introductory text (read from front to back) or as a reference tool (read as single sections). It begins with a section that presents an overview of light, including a historical perspective of light in buildings, the physics of light, human response to and perception of light, its sources, and a conceptual model for designing with daylighting. The second section focuses on the form and siting of buildings. The third section, on fenestration, describes design considerations and strategies, the effects of the geometry of the openings, glazing options and reflectors, and integration with electric lighting systems. Analysis techniques are described in the final section. These analyses cover preliminary design, physical models, graphic techniques, illuminance calculations, cost savings, and computer programs. The appendix is a collection of the basic analysis tools and tables necessary to enable the reader to design with daylight immediately, without costly or complicated equipment.

One of the most interesting parts of this book is the first chapter, "Historical Response." Here Moore briefly surveys the incorporation of daylight in buildings at various points in history. Beginning with Egyptian and Greek architecture, he describes the use of daylight in both domestic and civic buildings. He concludes this survey with some brief remarks on postmodern architecture. The discussion on preindustrial periods of architecture is further enhanced by numerous illustrations of well-known buildings of those times. The traditional plan and section drawings are supplemented by other drawings that explain structural systems, the light path, and three-dimensional representations of the building. The weakest part of this survey is the last discussion of architecture of the industrial and post-industrial periods. Because no illustrations support the text in this part, the powerful comparison between the modern and traditional attitudes towards environment (especially light), space, and structure cannot be made visually. Had he used specific buildings, accompanied by illustrations, as examples of this difference in attitude this discussion would have been clearer and stronger. Similarly, the concluding remarks on postmodernism and the future would have benefited from the inclusion of well-known examples. Despite this weakness, the historical overview is one of the most innovative parts of the book. It clearly establishes the context within which the issues of light and energy can be understood. From this context the incorporation of daylight in buildings can be viewed as critical to their aesthetics and meaning.

The historical survey is followed by a chapter on the basic principles of light. Though he presents no new information, Moore draws on his experience as an educator to make this information more meaningful to the reader. He explains the behavior of light using analogies that are more easily visualized than the light which they represent. An example of this is the explanation of luminous flux: the time rate of flow of light, as defined in the glossary, is shown to be similar to the water flow rate from a sprinkler head, measured in gallons per minute. His lighting terminology and numerous accompanying diagrams are both clear and concise, and are presented in a manner that is easily understood by nonscientists.

Clarity also characterizes Moore's discussions of human vision and perception and natural sources of light. Each discussion is brief, yet covers the basic principles needed for daylighting design. For the reader seeking a more detailed explanation, the standard texts on lighting are referenced at the end of each section.

In the final chapter in the introductory section, Moore explains two conceptual models for describing the behavior of daylight in buildings. He argues that the typical "source-path-target" model is not an accurate description of the behavior of light. Rather, he presents the case for using the "luminance × apparent size" model (though the name is not as catchy) as a truer depiction of the behavior of light. He further explains this model by using it in an analysis of daylighting strategies used by Alvar Aalto in six libraries.

The second and third sections present concepts related to the actual design of a daylit building. This discussion is patterned after many design processes--beginning with the site, moving to the form or massing of the building, and concluding with fenestration design. In these sections, both concepts and tools for designing are described and explained, such as the use of a sundial. How the tools work is explained, followed by a step-by-step method for their use. The use of the tool--in the case of a sundial, to plot site obstructions of the sun and sky--is related to the importance of knowing the lighting potential of each site. For example, the lines on the sundial are explained in terms of the sun's position in the sky. Moore discusses the design of the fenestration in a similar way, describing the design, relating it to the light levels within a space, and introducing the section graph, the typical means of representing the distribution of light. The only drawback to this central portion of the book is that it contains only a few buildings as examples of different daylighting design strategies. Those that are presented are quite helpful, but do leave one longing for more.

The final section of *Concepts and Practice* surveys different techniques and tools for analysis. This survey describes each method and its application, often with step-by-step instruction for its use. Moore discusses each method with a critical eye, discussing both the positive and negative aspects of each, including its ease of use, availability, and the assumptions made by its designer. This section of Moore's book will serve as a valuable handbook and reference for the architect in the process of designing a daylit building.

In summary, Moore has written a book on daylighting that will be quite useful to both the practicing architect and the student of architecture. Though the primary audience for this book is the designer who has little practical knowledge of architectural daylighting, the well-versed daylighting designer will also find the informative style quite useful when communicating with those less knowledgeable. *Concepts and Practice of Architectural Daylighting* is a welcome addition to the bibliography on lighting. It won't gather dust on the shelves of the libraries of interested designers, but will become dog-eared and ragged with use.

Reviewed by Virginia Cartwright
Department of Architecture
University of Oregon
Eugene, OR 97403

Passive Solar Journal, 3(4), 439-440 (1986)

About the Contributors

Mari Adegran is an architect with Columbus Architects in San Francisco. She has worked as a Research Associate at the Lawrence Berkeley Laboratory and as a designer with Peter Calthorpe Associates. Mari received her architecture degree from the Royal Institute of Technology in Stockholm in 1985. Her current interests lie in the integration of energy conservation techniques into design of high quality multifamily housing.

Brandt Andersson is a Staff Scientist in the Building Systems Analysis Group at Lawrence Berkeley Laboratory. He has focused on nonresidential building analysis for the past five years and has published papers on building energy analysis, post-occupancy evaluation, daylighting, climate analysis, and microcomputer software. Brandt received his master's degree in architecture from the Massachusetts Institute of Technology in 1977 and served as a Guest Researcher at the Royal Institute of Technology in Stockholm in 1981.

J. Douglas Balcomb is a Distinguished Research Fellow at the Solar Energy Research Institute on leave of absence from the Los Alamos National Laboratory. He received the ASES Passive Pioneer Award in 1984 and Charles Greeley Abbott Award in 1985 to honor his role "as foremost contributor to the development of passive solar calculations."

Herb Beatty, a former homebuilder, is Senior Consultant for the Solar Energy Associates, a solar consulting and distribution firm in Fort Myers, Florida. Previously he was Project Manager for the Mid-America Solar Energy Center in Minnesota. He is a graduate of the University of Minnesota with a BBA in Industrial Administration.

Virginia Cartwright is an Assistant Professor of Architecture at the University of Oregon in Eugene. She does consulting and research on daylighting design and is on the Executive Board of the Daylighting Network of North America.

Richard L. Crowther was elected a Fellow of the American Institute of Architects in 1983 for applied research in architecture. His completed architectural projects through a period of 50 years are located throughout the United States and Mexico. His architectural and energy conservation concepts and solar and natural energy writings have been widely published in numerous professional journals and books.

Wayne Place is an Associate Professor of Architecture at North Carolina State University. His research focuses on the integration of roof aperture daylighting systems into nonresidential buildings, extending earlier work at Lawrence Berkeley Laboratory on the issues of daylighting analysis, evaluation, and integration with other building systems. He holds a doctorate in physics from the University of North Carolina as well as a master's degree in architecture from North Carolina State. Wayne is also a registered Professional Engineer and has done extensive structural design work with Synergetics in Raleigh.

David K. Robertson is currently a Mechanical Engineer for the Property Control Division of the State of New Mexico. He was a Research Engineer at the University of New Mexico for nine years, specializing in energy conservation. He received a BSME in 1977 from the University of New Mexico. He is a registered Professional Engineer and a member of ASHRAE.

AUTHOR INDEX TO VOLUME 3

A

Adegran, M., 349-386
Anderson, R., 33-76
Anderson, B., 349-386

B

Balcomb, J. D., 221-248, 333-348
Beatty, H., 419-434
Burch, J. D., 149-177
Butler, S., 179-190

C

Cartwright, V., (book review), 435-438
Cook, J., 3-31, 115-123
Crowther, R. L.,329-332

D

Duffy, J., 77-97

F

Funaro, G., 291-320

G

Guerin, D., 179-190

H

Hedstrom, J. C., 125-148
Hill, D. D., 277-290
Howard, B. D., 249-276, (book review), 321-323
Hunn, B. D., 125-148
Hunter, K. C., 191-206

K

Kirkpatrick, A. T., 277-290

M

Millet, M. S. (book review), 105-111
Milne, M., 99-104

N

Neeper, D. A., 213-219

O

Odegard, D., 77-97

P

Peterson, J. L., 125-148
Place, W., 349-386

R

Reynolds, J., 207-210
Robbins, C. L., 191-206
Robertson, D. K., 387-418

S

Stokes, K. W., 277-290

PASSIVE SOLAR JOURNAL, 3(4), 443-444, (1986)

SUBJECT INDEX TO VOLUME 3

A

Adobe, performance of in residential buildings, 387-418
Air-Core system. *See* Hollow masonry heat storage
Analyses, of thermal models, 163-167

B

Building geometries, natural convection flow in, 36-41

C

Compendium, of daylight data, 191-206
Computers, use of in passive solar design, 99-104
Contributors, about, 113-114, 211-212, 325-326, 441-442
Convection. *See* Natural convection
Cooling. *See* Evaporative cooling

D

Data-model matching, for monitoring building thermal energy, 167-172
Daylight
  data describing, 191-206
  upholstery textile performance following exposure to, 179-190
  use of in architecture (book review), 105-111
Daylighting
  architectural, concepts and practice of (book review) 435-438
  in public library, 349-386
Department of Energy. *See* Level B passive solar monitoring program
Design, passive solar, use of computers in, 99-104
Development of passive solar technology in United States, 1976-1986, 333-348
Direct gain approach to solar architecture (book review), 207-210
Direct system, compared with heat pump in evaporative cooling, 3-31

E

Evaporative cooling
  direct and two-stage systems compared with heat pump in, 3-31
  using thermal storage, 125-148

F

Florida, design, construction, and performance of passive solar home in, 419-434

H

Heat pump, compared with direct and two-stage system in evaporative cooling, 3-31
Heat transfer, natural convection
  between building zones, 54-63
  through building envelope, 41-43
Holistic view, of solar design, 329-332
Hollow masonry heat storage, for thermal storage, 249-276
Horizontal surfaces, heating and cooling of, 47-50

I

Infiltration levels, used in determining size of solar collection area, 221-248
Italy, passive solar building in, 291-320

L

Level B passive solar monitoring program, compared with SLR for prediction of performance, 77-97
Library. *See* Public Library

M

Macrodynamic and macrostatic simulation, of building thermal energy, 155-159
Models, for building thermal energy 155-159
Monitoring building thermal energy, methods for, 149-177

N

Natural convection, applications of in solar building, 33-76, 277-290

P

Performance
  Level B monitoring program compared with SLR for prediction of, 77-97
  of passive solar home in Florida, 419-434
Public Library, daylighting on, 349-386

R

R-values, used in determing size of solar collection area, 221-248
Regionalist architecture, 115-123
Research, directions for, 213-219
Residential buildings
  in Florida, performance of, 419-434
  performance of thermal mass materials in, 387-418

S

Single building zone, natural convection through, 43-63
Solar collection area, use of R-value and infiltration levels in determining size of, 221-248
Solar design, holistic view of, 329-332
Solar load ratio (SLR), prediction of performance using, compared with Level B monitoring data, 77-97
Sunspace primer (book review), 321-323
Surface roughness, effect of on natural convection, 51-53

T

Tests, for building thermal response, 159-163
Thermal energy, in buildings, methods of monitoring, 149-177
Thermal mass materials, in residential buildings, performance of, 387-418
Thermal storage
  evaporative cooling using, 149-177
  hollow masonry heat storage for, 246-276
Triangular enclosures, natural convection through, 53-54
Two-stage system, compared with heat pump in evaporative cooling, 3-31

U

United States, passive solar development in, 1976-1986, 333-348
Upholstery textile, performance of following exposure to daylight, 179-190

V

Vertical surfaces, heating and cooling of, 43-50

PASSIVE SOLAR JOURNAL, 3(4), 445-447 (1986)

COLLECTIVE CONTENTS TO VOLUME 3

Volume 3, Number 1, 1986

Editorial 1
P. McFadden and R. Jones

Evaporative Cooling in Phoenix: Direct and Two-Stage Systems Compared with a Heat Pump 3
J. Cook

Natural Convection Research and Solar Building Applications 33
R. Anderson

Solar Load Ratio Design Tool Predictions Compared to Level B Monitoring Data 77
J. Duffy and D. Odegard

Opinion/ Passive Solar Sunset: Predicting Our Own Demise 99
M. Milne

Book Review/ Daylight in Architecture by Benjamin Evans 105
M. Millet

About the Contributors 113

Volume 3, Number 2, 1986

Opinion/ A Charter of Regionalist Architecture 115
J. Cook

Evaporative Cooling Using Thermal Storage 125
J. L. Peterson, B. D. Hunn, and J. C. Hedstrom

Building Thermal Monitoring Methods 149
J. D. Burch

Upholstery Textile Performance Following Exposure to Daylight 179
S. Butler and D. Guerin

Daylighting Data Compendium 191
C. L. Robbins and K. C. Hunter

Book Review/Solar Architecture: The Direct Gain Approach 207
J. Reynolds

About the Contributors 211

Volume 3, Number 3, 1986

Opinion/Solar Buildings Research: What are the Best Directions? 213
D. Neeper

Conservation and Solar Guidelines 221
J. D. Balcomb

The Air-core System for Thermal Storage 249
B. Howard

Natural Convection in a Passive Solar Building 277
A. Kirkpatrick, D. Hill, and K. Stokes

Passive Solar Buildings in Italy 291
G. Funaro

Book Review/The Sunspace Primer — A Guide for Passive Solar Heating 321
B. Howard

About the Contributors 325

Volume 3, Number 4, 1986

Editorial

Remembering John Yellott 327
R. Jones

Opinion

Solar Design: A Holistic View 329
R. Crowther

Passive Solar in the United States: 1976-1986 333
J. D. Balcomb

Daylighting in the Mt. Airy Public Library 349
M. Adegran, B. Andersson, and W. Place

The Performance of Adobe and Other Thermal Mass Materials in Residential Buildings 387
D. Robertson

A Passive Florida House 419
H. Beatty

Book Review

Concepts and Practice of Architectural Daylighting 435
V. Cartwright

About the Contributors 439

Author Index to Volume 3 441

Subject Index to Volume 3 443

AMERICAN SOLAR ENERGY SOCIETY

Susan M. Burley, Executive Director
2030 17th Street
Boulder, Colorado 80302

BOARD OF DIRECTORS

Bruce D. Hunn, Chair*
University of Texas
Austin, Texas

John S. Reynolds, Vice-Chair*
University of Oregon
Eugene, Oregon

William A. Beckman
University of Wisconsin
Madison, Wisconsin

Karl W. Boer
University of Delaware
Newark, Delaware

Francis de Winter*
Altas Corporation
Santa Cruz, California

Fred S. Dubin
Dubin-Bloome Associates
New York, New York

Joe Farber, Ex-Officio
Newport Beach, California

Gary J. Jones
Sandia National Laboratory
Albuquerque, New Mexico

Robert W. Jones
Los Alamos National Laboratory
Los Alamos, New Mexico

Harry Gordon, Secretary*
Burt Hill Kosar
Rittlemann Associates
Washington, D.C.

Marvin Van Der Pol, Treasurer*
Solar Energy Research Institute
Golden, Colorado

Edward Lumsdaine
University of Michigan
Dearborn, Michigan

Pamm McFadden
Elements Design Group
Boulder, Colorado

Frederick H. Morse
U.S. Department of Energy
Washington, D.C.

Mike Nicklas
Innovative Design
Raleigh, North Carolina

Paul Notari*
Solar Energy Research Institute
Golden, Colorado

Blaine F. Parker
University of Kentucky
Lexington, Kentucky

Bruce Wilcox
Berkeley Solar Group
Berkeley, California

Rowland Winston
University of Chicago
Chicago, Illinois

*executive committee member

PASSIVE ARCHITECTURE AND CONSTRUCTION DIVISION

Susan M. Burley, Acting Secretary
2030 17th Street
Boulder, Colorado 80302

BOARD OF DIRECTORS

Pamm McFadden, Chair
Elements Design Group
Boulder, Colorado

Gary Bailey
Innovative Design
Raleigh, North Carolina

Cris Benton
University of California
Berkeley, California

Polly Cooper
San Luis Obispo Solar Group
Santa Margarita, California

Jim Brown, Vice-Chair
Spring Valley, California

John Duffy
University of Lowell
Lowell, Massachusetts

John Lu
Tennessee Valley Authority
Chattanooga, Tennessee

Alex Wilson
A. T. Wilson Associates
Brattleboro, Vermont

Join the

American Solar Energy Society

Help yourself while you help the cause of Solar Energy.

We invite you to become a member of ASES and join other solar professionals united to advance the cause of U.S. energy independence by adoption of solar energy technologies.

Here are some of the services you will come to enjoy as an ASES member:

- Regular forums for the exchange of technical ideas between professional collegues.
- ***Advances in Solar Energy***, a compendium of the latest R&D developments in solar energy, authored by select ASES members and published annually by the Society for distribution worldwide.
- Two major technical conferences each year (with published proceedings) presented especially for ASES members and offered to them at special reduced prices.
- A quarterly ***Passive Solar Journal*** in which ASES members may publish their ideas and keep abreast of state-of-the-art developments in this field.
- A quarterly Newsletter with a special technical feature in each issue.
- A wide variety of technical publications offered to ASES members at special reduced prices.
- Special committees and councils providing ASES members the means to voice their views and collectively establish positions on given issues related to solar energy.

ASES needs your support. With the world's diminishing attention to renewable energy development, it is more important than ever that our nation's number one professional solar society remain strong. We can make great strides with your help. Show your commitment and join ASES today. Simply fill in the application below and submit it to the **American Solar Energy Society**; 2030 17th St.; Boulder, CO 80302. For additional information call (303) 443-3130.

ASES Membership Application

Name ____________________

Title ____________________

Company (if applicable) ____________________

Address ____________________

____

Signature

____

Please register me as a:

☐ Full Member ASES only ($50)

☐ ASES + ISES* member ($85)

☐ Full member and subscription to *Passive Solar Journal* ($75)

☐ Check enclosed (payable to ASES)

☐ Visa ☐ Mastercard ☐ AE

No. ____________ Exp. Date ________

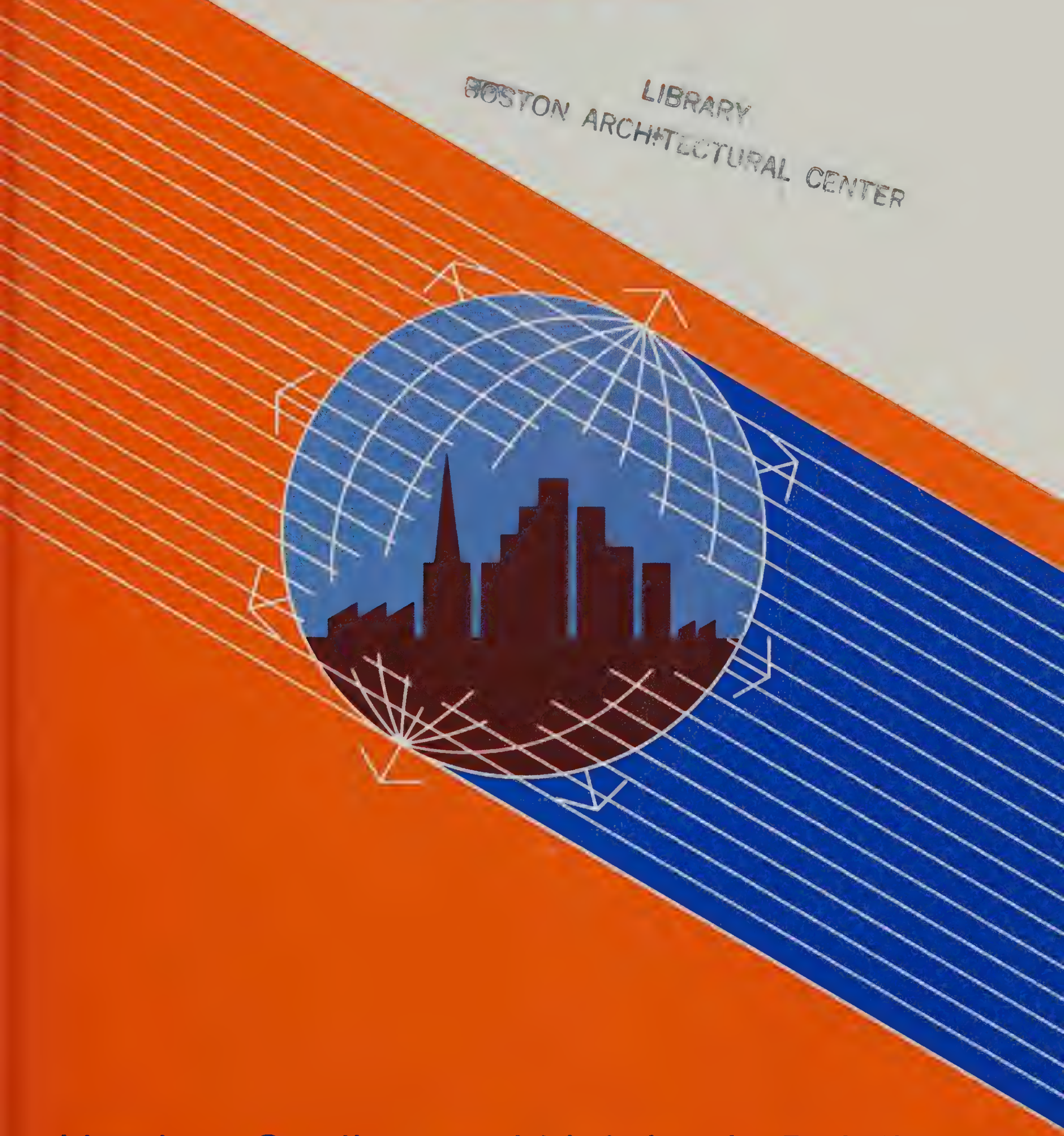
*International Solar Energy Society ASES international affiliate. (Dues include subscription to ***Solar Energy Journal***.)

DEN: PASJDP 4(2) i-iv, 123-235(1987)
N: 0277-6456

Passive Solar Journal

Volume 4 , Number 2, 1987

LIBRARY
BOSTON ARCHITECTURAL CENTER



Heating, Cooling, and Lighting in Buildings

Passive Solar Journal

Official Journal of the Passive Architecture
and Construction Division of the
American Solar Energy Society, Inc.

Editor-in-Chief

ROBERT W. JONES
Los Alamos National Laboratory
Mail Stop J577
Los Alamos, New Mexico 87545

Managing Editor

NANCY S. REECE
Solar Energy Research Institute
1617 Cole Boulevard
Golden, Colorado 80401

Consulting Editor

JEFFREY COOK
Arizona State University

Associate Editors

DENNIS A. ANDREJKO
State University of New York

J. DOUGLAS BALCOMB
Los Alamos National Laboratory

CHARLES C. BENTON
University of California at Berkeley

SUBRATO CHANDRA
Florida Solar Energy Center

EUGENE CLARK
Trinity University

MICHAEL J. HOLTZ
Architectural Energy Corp.

BION D. HOWARD
National Association of Home Builders

BRUCE D. HUNN
University of Texas

DONALD A. NEEPER
Los Alamos National Laboratory

RICK SCHWOLSKY
Grafton Builders

C. BYRON WINN
Colorado State University

AIMS AND SCOPE

The **Passive Solar Journal** is the official journal of the Passive Architecture and Construction Division of the American Solar Energy Society, Inc., the United States Section of the International Solar Energy Society. This organization has sponsored major national and international passive conferences. The **Journal** is guided by a distinguished editorial board, an international panel of advisors, and expert peer reviewers.

The purpose of the **Passive Solar Journal** is to stimulate and support the flow and exchange of research and professional information. The **Journal** is intended to become the archival record and the standard international reference for the field, with principal directions and issues documented in illustrated and referenced presentations. Annual indexes provide detailed cross-reference access. The **Journal** contains full-length articles, book reviews, and opinions that meet the highest standards of verbal and graphic communication. The scope of subject matter is passive solar heating, passive cooling, and natural lighting plus related subjects including the following:

Advanced concepts
Building climatology
Codes and standards
Community planning
Component design
Computer methods
Conservation
Construction details
Control systems
Daylighting
Design tools
Direct gain
Domestic hot water
Earth coupling
Economic analysis
Education
Energy budgets
Energy storage
Evaporative cooling
Historical examples
Hybrid systems
Indirect gain
Indoor air quality
Instrumentation
Integration and optimization
Landscaping
Lifestyles and needs
Market development
Movable insulation
Phase change materials
Photovoltaic interface
Radiation resources
Retrofits
Roof ponds
Selective surfaces
Shading
Simulation
Sky radiation
Solar architecture
Solar greenhouses
Sunspaces
Testing and monitoring
Thermal comfort
Thermal networks
Thermosiphons
Trombe walls
Underground climate
Urban design
User evaluation
Ventilation
Window systems

Passive Solar Journal
Volume 4, Number 2, 1987

Contents

Opinion

On Energy, Vernacular Architecture, and the Education of Third World Architects in the West 123
R. Schoen

Articles

Architectural Integration of Solar Systems for Domestic Water Heating 129
E. Ishai

Human Migration in Solar Homes for Seasonal Comfort and Energy Conservation 143
R. Crowther

Solar Access in Boulder, Colorado 171
P. Pollock

Solar Irradiance on Vertical Surfaces 187
T. Stoffel, E. Maxwell, R. Bird, and D. Myers

Superinsulated Houses in the United Kingdom 211
J. Littler and P. Ruyssevelt

Book Review

New England Solar Energy Atlas 225
T. Stoffel

Events 231

About the Contributors 233

Passive Solar Journal, 4(2) 123-127 (1987)

Opinion

On Energy, Vernacular Architecture, and the Education of Third World Architects in the West

Richard Schoen
Graduate School of Architecture and Urban Planning
University of California
Los Angeles, CA 90024

Interest in vernacular architecture and its relationship to energy and resource-responsive design is on the increase, particularly in the developing world. While we have yet to be able to power tractors and busses with the sun, incorporating the lessons of vernacular architecture as the foundation for resource-responsive architectural design can help free fossil fuels for those critical applications. *Natural Energy and Vernacular Architecture*, Hassan Fathy's new book, helps confirm the connection between resources and the vernacular that many in American schools of architecture believe to be an integrated design approach. Fortunately, interest in that connection appears strongest among graduate students from developing countries. Unfortunately, that enthusiasm is not always shared by clients and housing ministers when the students return to their home countries. While many countries have effective, even universally required, limits on what can be done to valued historic buildings, less concern, even understanding, is shown about how lessons of those buildings can be incorporated in new construction.

Nowhere is the issue clearer than in countries where architects rush to import western forms and construction materials often inappropriate to climate, much less culture. Native building forms and materials, which have been in consonance with their micro-environment for hundreds of years prior to Willis Carrier's great invention, are often totally supplanted, while western forms are associated with status and modernity. Building "in the old manner" is an idea often met with derision. Those forms may also be associated with the "old days" or even "colonial times." However, architecture entirely limited to literal reproduction of both vernacular form and material may be equally inappropriate in an age of communications. At best, a dilemma exists. Or is there more?

One can also view the preceding difficulties as challenges. Without suggesting that architects or architectural education can impact all dimensions of this problem, a very useful contribution can be made if the educational process is sensitive both to the unique cultural attributes of the foreign student and the problems he or she faces in attending a university in the West. Through those students, we in the West can also better understand what we "teach," since it can be argued that much of contemporary, energy-responsive, solar architecture differs from its vernacular counterparts largely in that we can quantify and therefore predict performance while those long-ago builders could only know performance experientially. At the same time, we can assist those students in furthering that quantification in their own context as well as introduce them to contemporary architectural and urban design techniques and planning analysis in ways that will find receptive and appropriate application in their home countries.

These issues are one focus of discussion in the UCLA Graduate School of Architecture and Urban Planning's embryonic and still unofficial Institute for Architecture and Urban Design in the Developing World. Thus far, several educational concepts have begun to emerge. They include:

The "veil of language" must be dispelled early. While schools have the right to insist on adequate English language skills, too often difficulty in reading and especially speaking becomes a veil obstructing communication between otherwise intelligent and dedicated individuals — and one which harried faculty are often not willing to deal with. We must find means of dispelling it early in students' careers. We must encourage those students to speak up in seminar and provide them multiple opportunities to exercise their English in the least threatening way, by presenting their own work.

Newly acquired tools and techniques of analysis and design synthesis should be applied to problems and projects in their home countries, not to problems in St. Louis or San Diego, lest they return home with no experience in effecting the requisite socio-cultural and economic shifts required for those techniques to be relevant in their own national and regional contexts.

Where appropriate, expand the scale of problems to that of urban design of communities, towns, and cities, both new as well as renewed and infill. The problems of urbanization, immigration, overpopulation, and in some cases, desertification are all but overwhelming the colonial-based infrastructures of the Third World's major cities, where 13 of the world's 15 largest cities will be by the year 2000. As students have shown, much can be learned about both climatic and cultural responsiveness from the organically veined, self-shaded street patterns of Marakesh and the "*medinas*," or old cities, of Tunis, Algiers, Jerusalem, Cairo, and Jaiselmer.

Encourage "south-south" sharing among students from developing countries. That phrase, coined I believe by Erskine Childers, director of information for the United Nations Development Program, alludes to the great amount of mutual learning that can go on among developing countries and their students because of an innate understanding of common problems.

Encourage the best of Third World architectural graduate students to pursue advanced studies and research at the Ph.D. level and beyond. Much initial graduate work by these students is preoccupied with rediscovery and categorization of passive solar techniques inherent in their vernacular traditions. They need those extra years to be able to actively participate in the basic research and physical experimentation that can lead to the creation of quantified design guidelines for practitioners in their own countries, specific guidelines that can compete with the "spec sheets" of their local Carrier representative.

Showcase the work of Third World students wherever possible. Beyond interests in vernacular/energy/solar architecture and urban design, students from the United States and other western countries can learn much from their Third World peers. Fostering such interchange is in the best traditions of a great university.

Capitalize on modern communications techniques that will allow the university to remain in touch with and serve as a continuing resource to the graduated student returned home, and that individual to the university. This is a primary focus of the proposed institute at UCLA: it will be a **communications-based** activity. Several strategies to implement that objective have already been initiated.

Students must be challenged to integrate the lessons of their vernacular with the emerging demands of a post-industrial age of communications. We can only begin the process with vernacular forms and materials; both must then be re-expressed in a contemporary context to respond to requirements that simply did not exist in an earlier time. If, for example, an Egyptian student proposes in his thesis to settle displaced rural populations in expanded market towns or even totally new communities in the "new territories," it would not be sufficient for that student to, in effect, tell a skilled farmer from the Nile delta that he now must live literally in the mud huts of his ancestors, not when that farmer can hear Michael Jackson on his transistor radio and see the wonders of Cairo on his village television. To marry contemporary responses with lessons of the vernacular without insulting either has not often been done well and is perhaps the most difficult challenge facing Third World students and practitioners alike.

In this relatively brief era of oil oversupply, we have been given a respite to consolidate the phenomenal gains we have made as a profession, country, and world in energy conservation and to push for still further achievements in resource-responsive building and community development. That will be possible only if we can continue to learn and to help keep those concerns within the public's view.

There is much for us to learn from the lessons of vernacular architecture, and much that can charm the public in that regard, as a kind of "technology transfer" in reverse.

While in Egypt to make an invited presentation of a stand-alone community proposed by ARCO Solar founder Bill Yerkes and myself, at Umn El Uweinat, deep in the western desert of Egypt, near Uweinat Mountain, I had the good fortune of meeting Professor Fathy and perusing with him the original manuscript for his new book. I apologized for presuming to come to his country to design a new resource-responsive community (although our proposal insisted upon collaboration with Egyptian architectural firms and scientists). He smiled and observed, "That is quite OK. Sometimes a man must prove himself in another's village before he is accepted in his own."

Passive Solar Journal 4(2), 129-142 (1987)

Architectural Integration of Solar Systems for Domestic Water Heating

Edna Ishai
Faculty of Architecture and Town Planning
Technion-Israel Institute of Technology
Haifa, Israel

Abstract

Architectural designs are suggested for solar domestic water heating units (collectors and water storage tanks) in multifamily houses up to four stories. The designs are based on different combinations of standard units assembled to fit the different architectural types as designed by the Israeli Ministry of Housing. In addition, an approach is presented that suggests a unique design of the upper floor apartment with inclined roofs so the solar system becomes an integral part of the structure. Several solutions are suggested and compared.

INTRODUCTION

The use of solar energy for heating water for domestic purposes is a well-known, common technique in Israel and many other countries around the world. Domestic hot water solar units are designed and produced locally in Israel by different private companies with a large variety of types and methods. Their designs are usually uncontrolled from an aesthetic and architectural standpoint. The solar collectors and the water storage tanks are usually randomly assembled on the rooftops of the buildings. The result in many cases is unsatisfactory both architecturally and environmentally.

Analysis of the existing solar domestic hot water technology shows that the factors related to aesthetic deficiency include the variety of geometrical shapes, type of materials, and number of components involved; the uncoordinated arrangement of the system components on the roofs; the shape and height of the storage tank (in a single unit); the shape of the support system; and the variety of piping assemblies. Recently, because of the awareness of environmental quality, some limited improvements have been made to the arrangement of a system on the roof, the shape and height of the storage tank, and its combination with the solar collector. Nevertheless, these improvements only partially solve the problem of the exaggerated amount of visual shapes in the system; in many cases, the shape of the system's support and the general arrangement of several systems on a roof are still unsatisfactory (Figures 1 and 2).

Consequently, the objective of the work described here is to develop and suggest a systematic architectural approach for the design of solar domestic hot water units and their integration with the roof structure of the building. The solutions presented, summarized, and compared here are adaptable to standard houses of one to four stories in height.

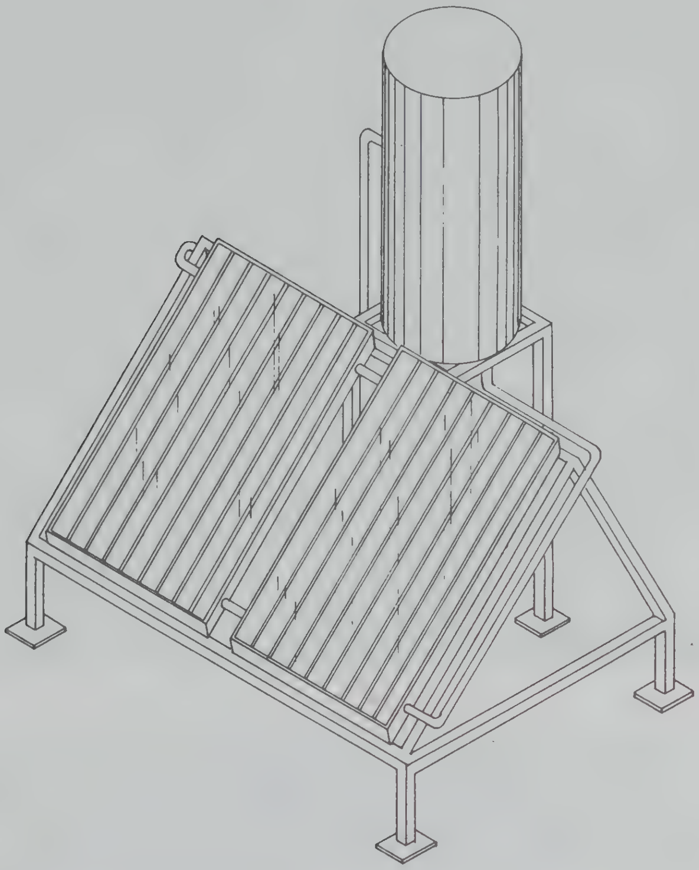


Figure 1. Existing solutions for domestic solar roof units – typical storage tank and collector

DESIGN CRITERIA

Component Sizes

Based on a survey of the functional needs and the local specifications adopted by the Israeli Standards Institute and the Ministry of Housing, the following quantitative characteristics were adopted for a design of a solar system for a single dwelling unit:

- Tank capacity - 120 l (32 gal)
- Tank dimensions - 105 cm height (41 in.)
  60 cm diameter (24 in.)
- Net collector area - 2.2 m^2 (24 ft^2)
- Collector tilt - 42°.

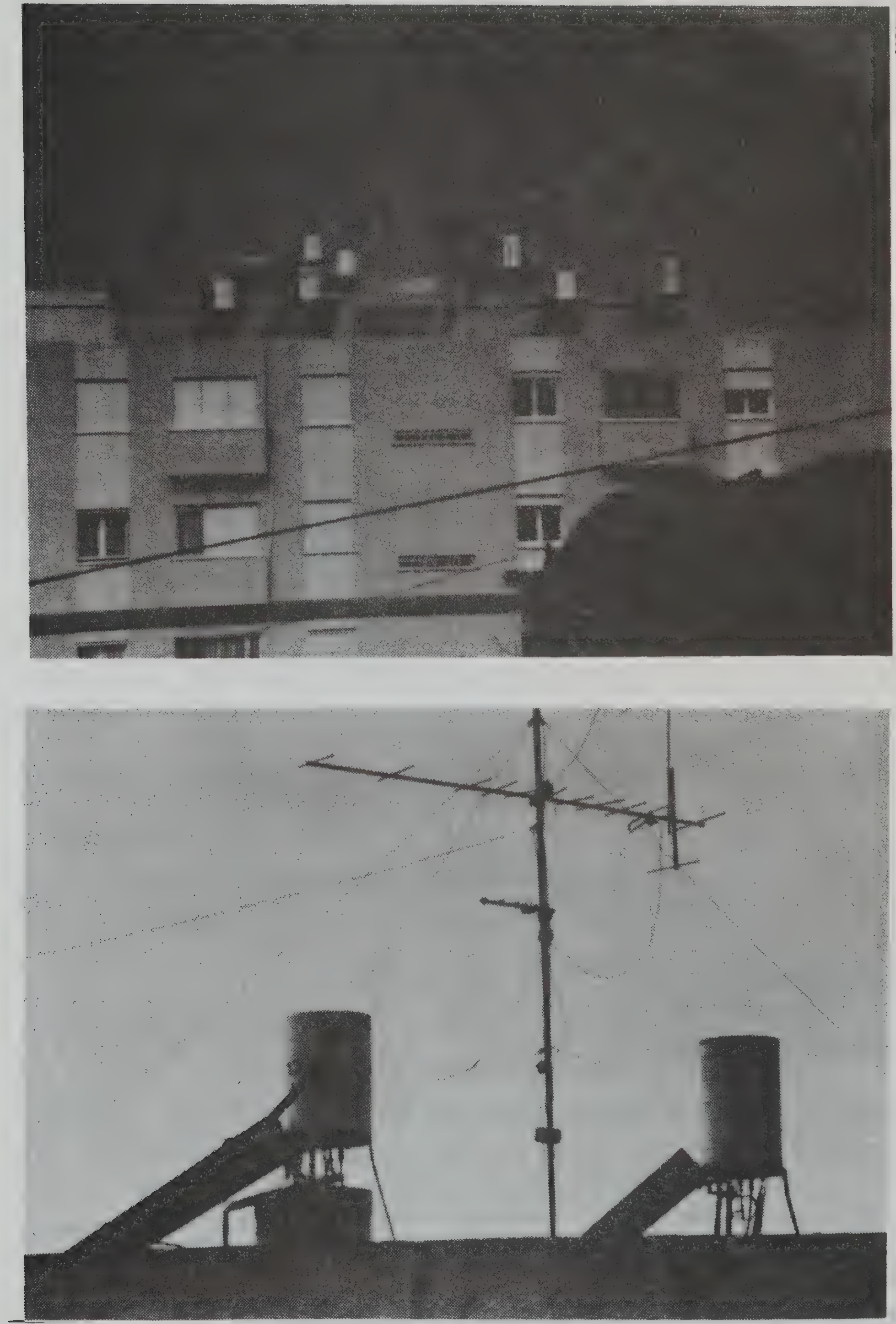


Figure 2. Existing solutions for domestic solar roof units - the uncoordinated arrangement of the system components on roofs

Most multifamily residential buildings in Israel have four stories. They can be divided into two groups: "row houses" with two apartments to a staircase on each floor and "square houses" with four apartments to a staircase on each floor. Examples of typical floor plans for each group are shown in Figure 3. Collector area needed for row houses is $2.2 \times 4 \times 2 = 17.6\ m^2$ ($189\ ft^2$); for square houses is $2.2 \times 4 \times 4 = 35.2\ m^2$ ($378\ ft^2$). The horizontal projections of these collector areas are $13.1\ m^2$ ($141\ ft^2$) and $26.2\ m^2$ ($242\ ft^2$), respectively.

Orientation

For a simplified and efficient arrangement of the solar systems on the building roofs, the orientation of the systems should be parallel to the building lines. This way the collectors will be aligned according to the building orientation from south-west to south-east. The resulting aesthetic improvement implies a small cost increase nationwide. In other words, if a building orientation deviates from direct south-north or east-west by more than ± 10°, an increase in the collector area should be made. For example, if the deviation is 30°, the increase in collector area should be 10%; for a 45° deviation, the increase should be 25%.

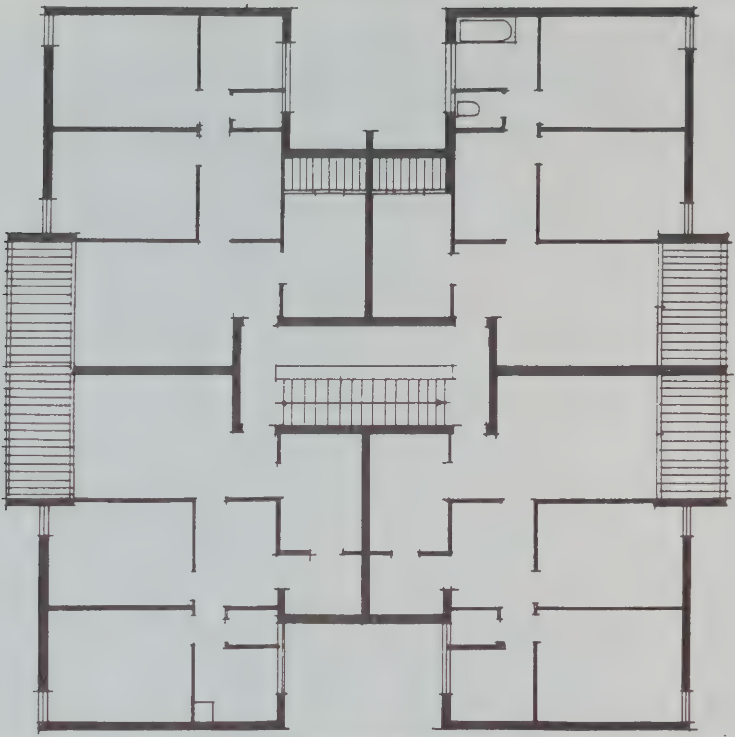
If buildings were randomly oriented, one could assume that in about 25% of all cases, no increase in collector area would be necessary. However, since the north-south orientation is generally preferred in Israel because of climatic considerations, it was assumed that about 50% of the buildings would not need any increase in collector area. The other 50% are assumed to be equally divided between two categories, those needing a 10% increase in collector area and those requiring a 25% increase.

The cost implication of such an increase in the collector area is approximately 3% and 7.5% for single solar units. This implies an increase of about 2.6% ($0.25 \times 3\% + 0.25 \times 7.5\%$) for the total cost on a national scale.

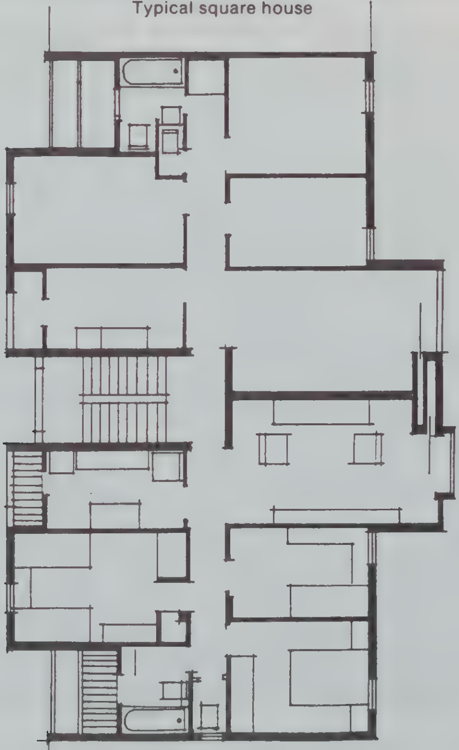
General Design Goals

The design solutions were developed under the assumption that the aesthetic appearance of solar systems can be improved by reducing

007993



Typical square house



Typical row house

Figure 3. Typical floor plans in row houses and square houses

the variety of visual shapes and materials, centralizing and consolidating the systems, and by integrating the system both visually and structurally in the building.

THE SOLUTIONS

Standard Row and Square Houses

Figures 4 and 5 present the suggested solutions for standard row houses; Figure 6, the solutions for the square houses; and Figure 7, typical cross-sections. These solutions demonstrate the modular design possibilities and their organization in the two types of buildings, as follows.

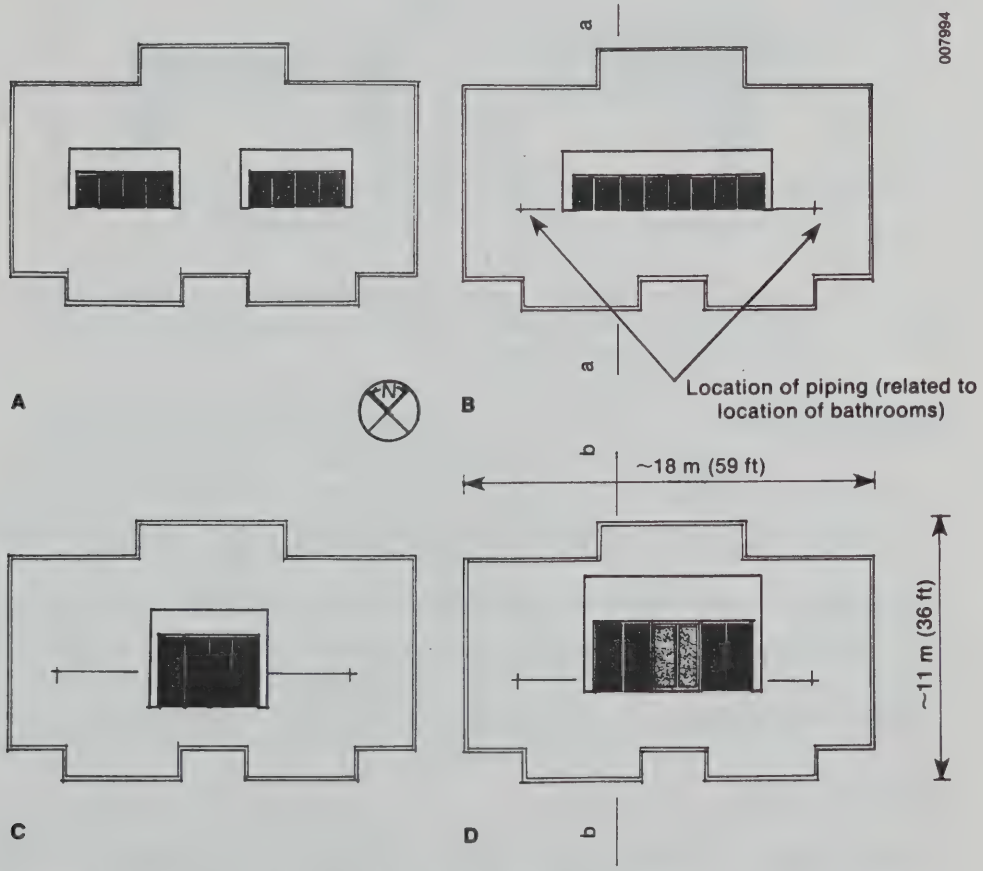


Figure 4. Plans for solutions of solar systems in standard row houses (east-west building orientations) (see Figure 7 for cross-sections)

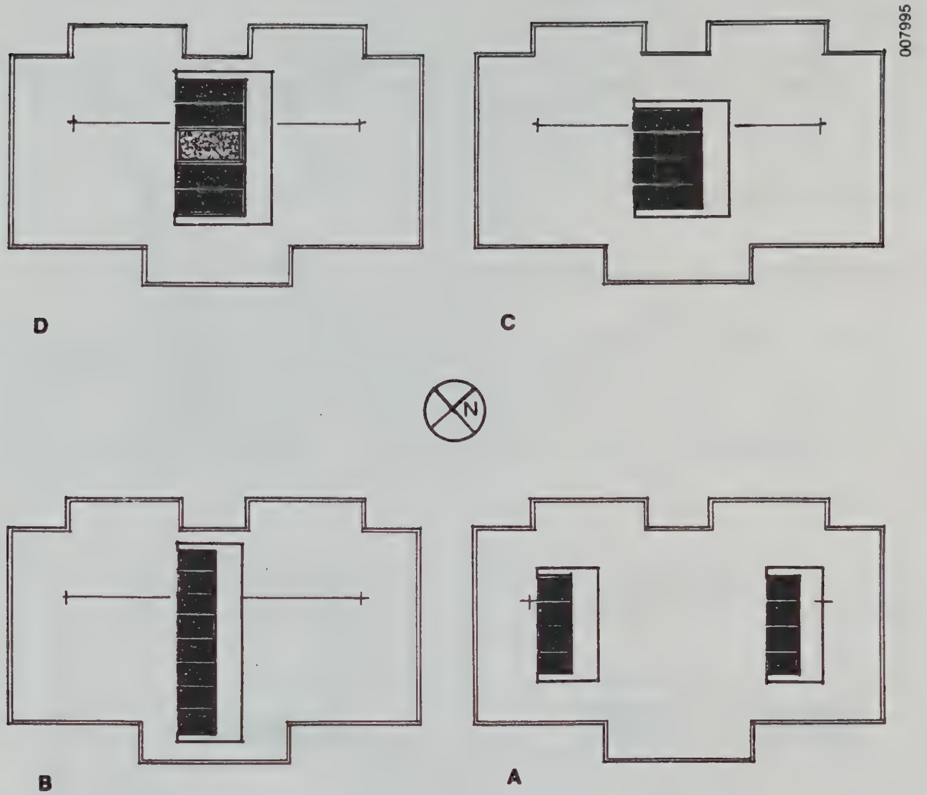


Figure 5. Plans for solutions of solar systems in standard row houses (north-south building orientations)

In row houses:

1. Two groups of four collectors in a row (see A in Figures 4 and 5).
2. A group of eight collectors in a row (see B in Figures 4 and 5).
3. A group of eight collectors stacked (see C in Figures 4 and 5).
4. A group of eight collectors stacked (see D in Figures 4 and 5). The space below creates a functional addition to the upper floor apartments (roof windows were added between the collectors).

In square houses:

1. Four groups of four collectors in a row (see A in Figure 6).
2. Two groups of eight collectors in a row (see B in Figure 6).
3. A group of 16 collectors stacked (see C in Figure 6).

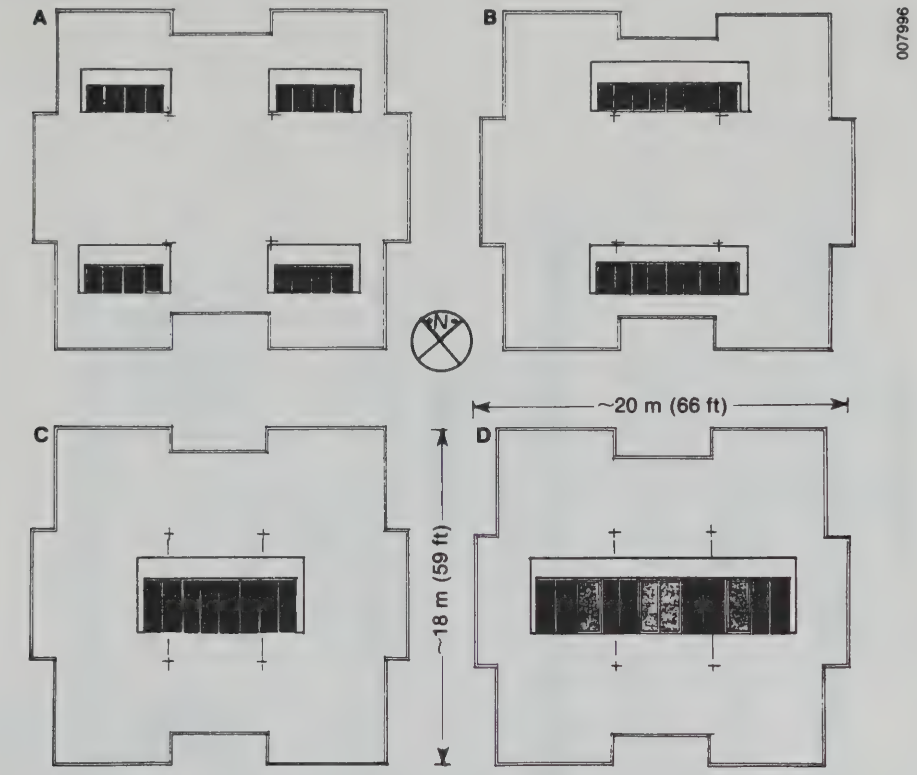


Figure 6. Plans for solutions of solar systems in standard square houses

4. A group of 16 collectors stacked (see D in Figure 6). The space below creates a functional addition to the upper floor apartments (roof windows were added between the collectors).

Integrated Solutions - Modification of Upper Floor Apartments

Figure 8 presents a few examples demonstrating a different approach. The basic concept here suggests a unique design of the upper floor apartments with an inclined roof so the solar systems become an integral part of the structure. This case involves an increase in the volume and quality of the upper roof apartments.

Figure 8 shows three possible solutions in this category in which different parts of the roof are inclined. These are only a few examples of the many possible integrated architectural solutions that could benefit from this approach.

007997

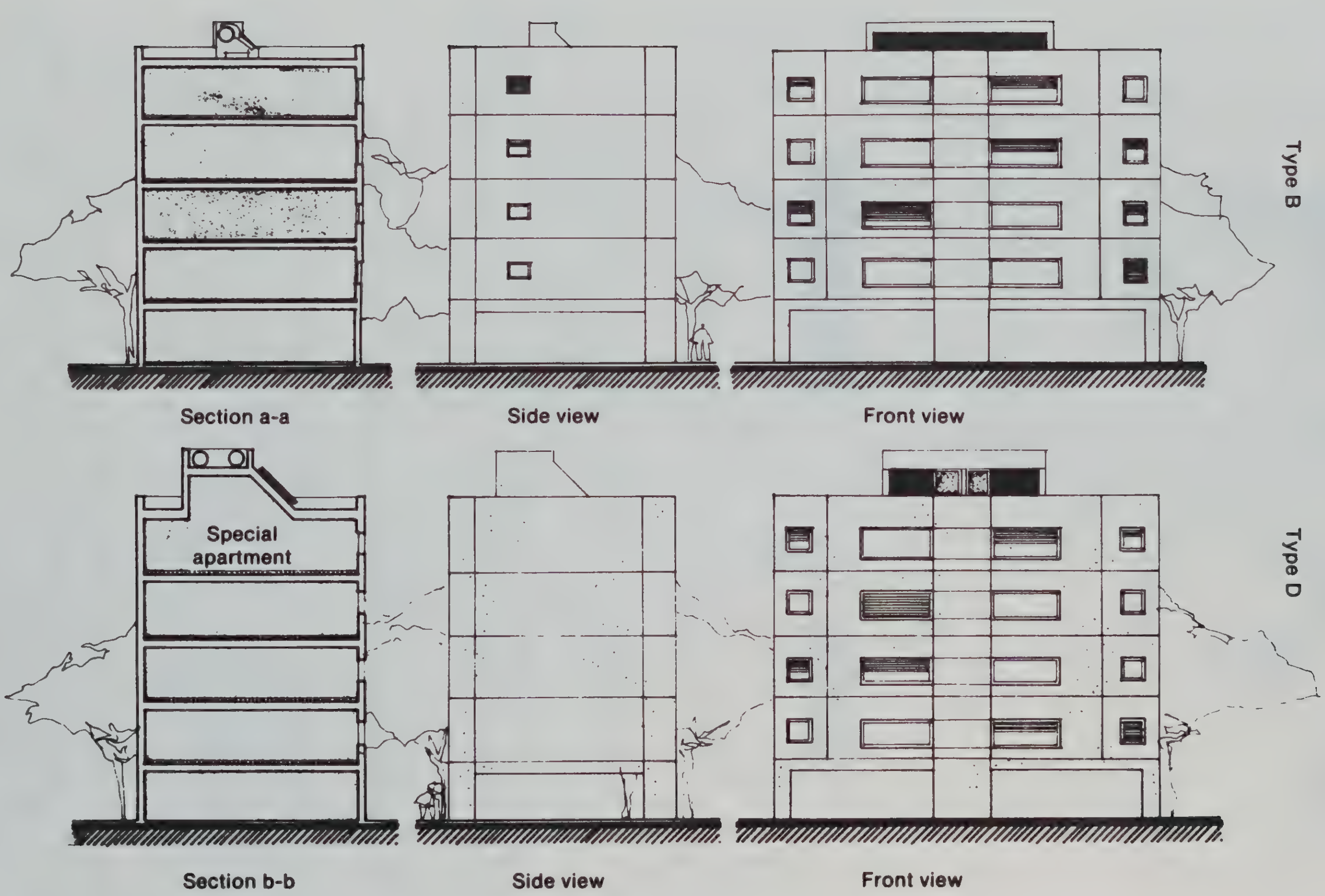


Figure 7. Typical cross-sections for solar systems solutions in standard row houses

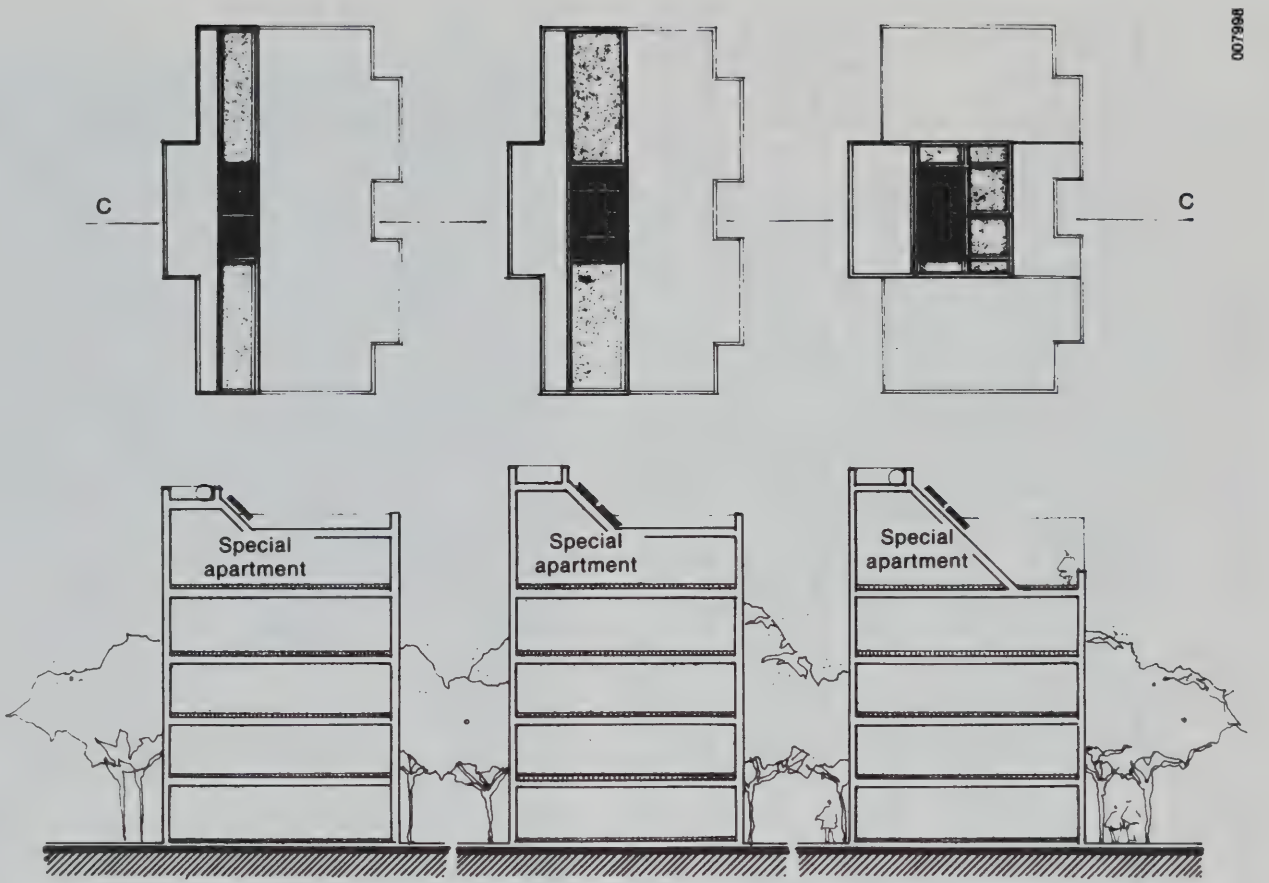


Figure 8. Examples demonstrating the integral solution approach

Evaluation of Solutions for the Standard Houses

The total cost of construction and operation of a solar system is a function of collectors, storage tank, piping and fitting, support, maintenance, and auxiliary fuel. Costs of the following factors may vary among the solutions suggested: extra length of piping and fittings (which influences the efficiency of the system), support modifications, additional and special features related to the specific solution, maintenance, and auxiliary fuel.

In the case of north-south oriented row houses (Figure 4), solutions B and D have some advantages. Solution B is visually compact and simple. It has a simple support system and is easy to maintain. Its main disadvantage is the extra length of piping. Solution D is also visually compact and simple. Its support system is more complex, and it has a similar extra length of piping, but its main advantage is related to the extra quality added to the apartment below (see section b-b in Figure 7).

In the case of east-west oriented row houses (Figure 5), solutions A and D have some advantages. Solution A is visually simple although not compact. Its main advantage lies in the savings related to its simple construction and the short piping required. The advantages of solution D are similar to those of the one represented in Figure 4.

In the case of square houses (see Figure 6), solutions B and D are preferable. Solution B is visually simple and relatively compact. It has a simple support system and is easy to maintain. Solution D has similar advantages to solution D in the row house (Figures 4 and 5).

SUMMARY AND CONCLUSIONS

Several solutions are suggested for the design of solar systems for domestic water heating. These solutions can be divided into two major categories. The first category involves adding modular units to the roofs of standard housing types with a minimum interference in the standard design (Figure 9); the second, modifying upper floor apartments to include inclined roofs so the solar system becomes an integral part of the structure (Figure 10). These solutions are compared and evaluated in this preliminary study; further economic evaluation and detailed architectural design are required.

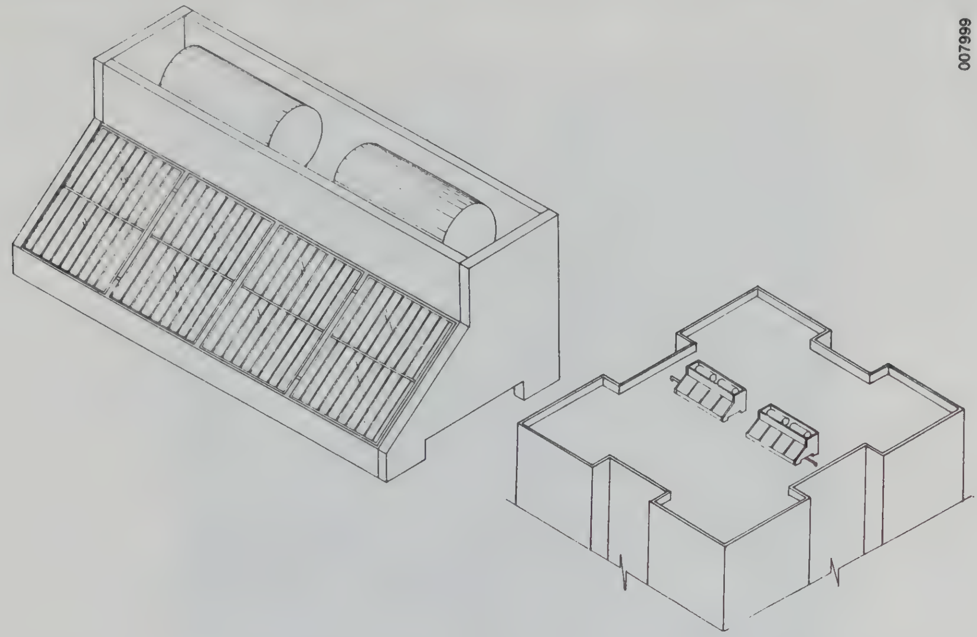


Figure 9. Suggested solutions: Example of an addition of modular units to the roof of standard housing

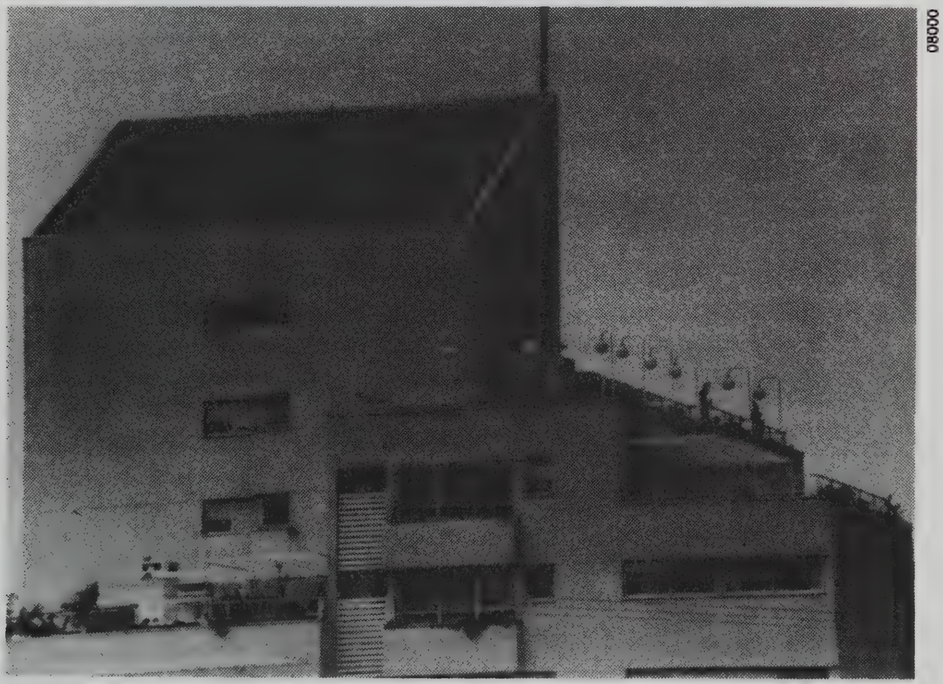


Figure 10. Suggested solutions: Example of special upper floor apartment with integral solar system

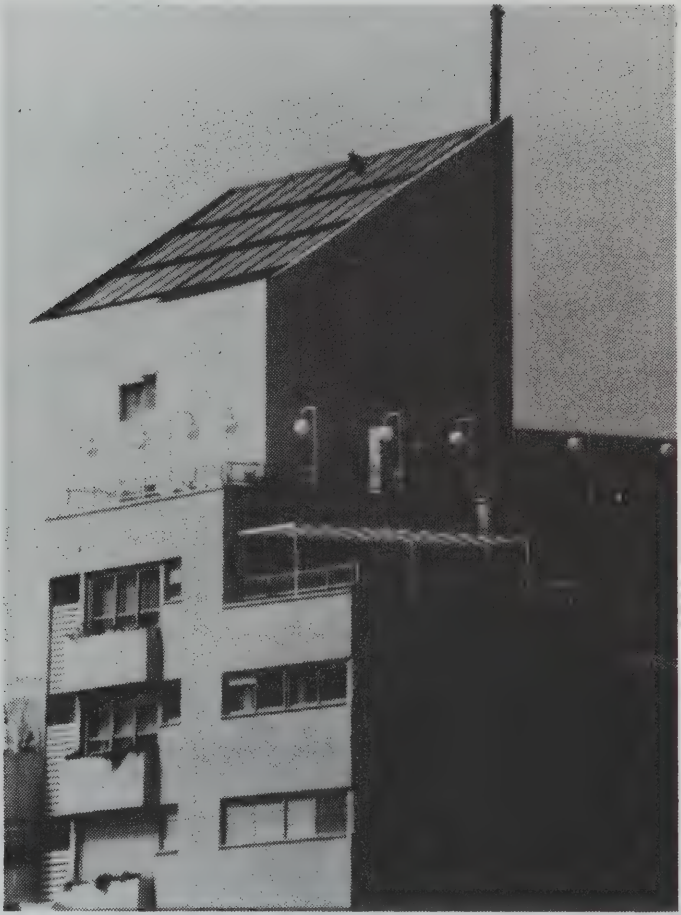


Figure 10. Suggested solutions: Example of special upper floor apartment with integral solar system (concluded)

Passive Solar Journal, 4(2), 143-169 (1987)

Human Migration in Solar Homes for Seasonal Comfort and Energy Conservation

Richard L. Crowther
401A Madison St.
Denver, CO 80206

Abstract

Every new and existing dwelling can benefit from spaces and migratory pathways that are responsive to and aligned with the natural energies of the building environment. Conceptual planning and architectural design attuned to these natural energies can increase comfort, energy conservation, and indoor and outdoor use of space. Of special importance is responsiveness to daily and seasonal microclimatic changes.

The aim of this article is to provide themes and examples especially related to human migration patterns as determined by activity and response to climate.

INTRODUCTION

Without arduous travel and crowded resorts, we can plan, design, and adapt our homes and properties for seasonal comfort, localized escape, and other compensatory satisfactions. Instead of going south for a winter break or north to cool off in summer, we can optimize the solar, daylighting, and climatic attributes of our homes and buildings.

The interaction among human response, architecture, site, and nature is critical to human vitality and well-being. Migration fulfills an innate need to be in phase with nature's dynamic processes of change, replenishment, and rejuvenation. Migration at home, broadening the spectrum of uses, comforts, and delights, is best accomplished through interior and exterior planning and design that emphasize solar, climatic, and earth-responsive architecture.

Older homes with migrational spaces that responded to comfort and function adequately served a past way of life. Before upgraded mechanical heating and cooling systems, persons moved within homes from place to place: to porches for gathering and sleeping, to basements or outdoors seeking comfort on hot summer days, and to sunrooms and solar-radiated spaces on cold days. Today our diverse and often informal lifestyles are still conducive to variety in migrational destinations. By incorporating natural energy-responsive technologies in design, materials, and strategies, we can enjoy the resulting physiological and psychological benefits and greater environmental self-sufficiency. Architecture of the past that expresses a conceptual diversity and sensitivity toward psychological and physiological needs can be retranslated and appropriately expanded within a contemporary solar and climate-responsive idiom. Unfortunately, many of today's "tight" well-insulated homes ignore the traditional migration opportunities as well as the natural energies available at the building site. In contrast to this approach, I suggest that migration for diverse uses of natural energy be restored to suit our design palate.

Our scope of perception and the enrichment of our psychological and physiological experience depend on the degree and diversity of our migration. All our senses come into play as we move about in space. Our adaptability, territorial gratifications of mind and body, and realizations at each destination are enhanced by migration, resulting in fulfillment of need and desire, and attainment of comfort. Functional activities alone may predominate, but our responses are influenced by the aspects of space; furnishings; sensory ambience of light, color, and texture; and internal and external views. The presence of others and degree of personal comfort and sensory satisfaction with sound, touch, and aroma motivate us towards certain spaces that we deem most suitable and accommodating.

DESIGN THEMES

Migrational Destinations

Migrational destinations within a structure are spaces more climatically suited than others to certain tasks or activities. The entire site and its interrelationship with the architecture and transient or destination-oriented migration should be considered, particularly as migration shifts seasonally. Optimizing use, comfort, and enjoyment both within the structure and the site should be the primary theme within conceptual design, planning, and subsequent design stages of a project.

For better or for worse, the surrounding environment influences seasonal outdoor migrational uses by means of shadows cast by neighboring landscaping, architecture, and other structures. Violation of privacy, odors, and noise from neighboring sources, and glare from nearby structures can be particularly disconcerting whether a person is inside or outdoors.

Enticing outdoor destinations offer benefits. Interior migration along the way through vestibules, halls, corridors, galleries, rooms, garden pathways, or up or down stairways also contributes to our emotional and perceptual experience.

Sunspaces, attached greenhouses, and atria can act both as migrational spaces for functional or leisure use and as daylighting and thermal zones. Sunspaces as interior migratory destinations offer the advantages of retained solar energy in thermal mass and tempering of ventilation air. Sunspaces can be modest sunrooms, spacious living spaces, central solar atria, north-side sunspaces radiated by south-facing clerestories, solar attics, solar spa rooms, greenhouses, swimming pool areas, and below-grade spaces that receive daylight and direct solar radiation.

Even visual or imagined migration facilitated by the ability to see from one interior space to another and to the outdoors stimulates our perceptions and psychological responses. Migration exercises our mind and body and affirms our sense of context, scale, and time.

Adaptability

Spaces within a home or building can serve many uses. Our challenge is how to plan and design spaces to best accommodate daylighting, penetration of solar warmth, and furnishings to serve these multiple functions. Adaptable environments increase the possibilities of varied activities alone or with family, friends, and others.

Forethought about the common factors that can serve many purposes is essential to optimizing indoor space use. The migrational pathways and patterns created by the architecture and the size, position, and location of furniture, equipment, and other interior elements predetermine our responsive behavior.

Light

Light plays a primary role in the formation and exercise of our behavioral decisions. We gravitate towards or away from light. Visual perception initiates our response, our direction, and the rapidity of migration toward or away from that which is illuminated.

Arrangement

We migrate within as well as between rooms or spaces. The larger, or more multistoried and divided, that an architectural interior may be, the greater are the migrational options. Basement areas, too often dismally subterranean, can be opened up to the exterior with below-grade courtyards, terraces, sunspaces, or openings around stairwells or through the floor above. Openings between floors create interest and expand the feeling of space, but noise and loss of privacy can be unwelcome trade-offs. Spatial openness invites migration, releases any stress caused by a sense of confinement, and allows for activities appropriate to an open setting.

Scale

The contemporary movement in architecture did much to bring the outdoors inside. Visual migration is enlarged in scale between indoors and outdoors by means of the larger glazed openings. Contemporary open planning also adds to interior scale.

The penetration of daylight through interior space creates a sense of scale through the definition of objects, spatial relationships, form, color, and texture. Diminution of scale makes us feel protected if indoor confinement does not constrain visual or physical escape. A differentiation in scale within the volumes and proportions of space adds interest to migratory ventures.

Functional Orientation

The orientation of spaces often prescribes their function. Any indoor or outdoor space can be planned and designed for any function, provided occupants can control the sun's direction and intensity and the climate.

South-facing unshaded patios, porches, balconies, porticos, verandas, terraces, archways, and courts receive maximum direct solar exposure year-round. Architectural overhangs, roofs, awnings, and trellises affect the amount of solar radiation received by and degree of shading of exterior walls and window openings. These elements influence the suitability of adjoining indoor spaces for certain tasks. Functions that specifically need daylight or adequate artificial light are especially affected.

In general, south exposures are most conducive to socializing, sunbathing, relaxing, reading, writing, conversing, eating, sewing, drying clothes, gardening, solar food drying, bathing, and swimming. East exposures are most suited to breakfast nooks and morning sunbathing, and preferable for late afternoon entertaining in hot seasons. West exposures can accommodate most activities if effective solar control is exercised. North exposures are most suitable for relaxing, sleeping, drawing, working, meditating, listening to music, exercising, and preparing food. Central thermal zones lend themselves to bathing, grooming, showering, washing clothes, exercising, and watching TV. These zones are ideal for saunas, retreat spaces, and darkrooms.

Clerestories, skyshafts, skylights, and roof monitors can architecturally change the daylighting and the effect of direct sunlight and energy on interior spaces. Sunlight can penetrate north or central interior spaces, giving them more of the attributes of south interior spaces.

SEASONAL AND DAILY DAYLIGHT AND THERMAL ZONES

Latitude, southern orientation, location, aperture size, type of glazing, and uninterrupted solar exposure determine seasonal and daily interior thermal zones. External reflections from horizontal, vertical, or other surfaces can add to interior solar gains. Shading or filtration will lessen interior solar gain.

The short daylight hours of winter contrast with the long daylight hours of summer. Our migrational options are fewer in winter, early spring, and late fall because diminishing hours of daylight and reduced temperatures make the outdoors less attractive. Unless care is taken in the distribution of heat to north zones or other spaces that tend to be cold, we curtail migration to them. The location and size of openings and the seasonal and daily influx of daylight and solar radiation with their concomitant effect on interior air convection also affect migrational behavior.

Winter: Daylight and Thermal Zones

During the winter, depending on latitude and time of day, the sunlight will obliquely enter southeast interior rooms and spaces in the morning. From about 9 a.m. to 3 p.m. the sun's radiation is optimal in terms of directly illuminating and warming interior spaces. In the afternoon the sunlight will obliquely enter southwest interior rooms and spaces.

Spring: Daylight and Thermal Zones

During spring, sunlight enters east rooms and spaces in the morning more directly than at other times of the year. At noon the sun's southern position provides less solar radiation than during the winter. Afternoon solar radiation directly enters west rooms and spaces more than at other times. Because of the buildup of thermal gains during the day, the west solar radiation tends to overheat the interior. Morning and afternoon activities are affected by more sun than in the winter; middle-of-the-day activities are subject to a moderate amount of solar gain.

Summer: Daylight and Thermal Zones

From dawn to dusk the low angle of the morning and afternoon sun in the summer affects the northeast, east, northwest, and west exposures, in that order. The high angle of the midday sun largely excludes direct solar radiation from interior spaces. Whereas south rooms and spaces receive little direct solar radiation, east and particularly west rooms and spaces bear the burden of thermal gains.

Fall: Daylight and Thermal Zones

For the most part, the sun's influence in the fall approximates that of the spring, but because of the sun-warmed earth of the summer the thermal gains will be additionally increased.

Outdoor Spaces

Use of outdoor spaces for various functions depends on the climate. Indoor spaces in well-insulated dwellings are more affected by solar orientation, architectural openings, and design than they are by outdoor conditions.

Some locations are subject to extreme climatic changes, while in others the changes are very moderate. In all locations, however, outdoor design can make space use more desirable in what normally might be regarded as uncomfortable conditions. Quasi indoor-outdoor spaces such as partially enclosed porches, balconies, patios, and courts offer protection from the elements, including the sun, that extends seasonal use. As the climate dictates, such spaces can be covered to diminish wind, control solar radiation, protect against rain or snow, and to moderate temperatures. Interior spaces that can be opened with patio doors to the outdoors exhibit similar but moderated thermal and comfort responses to changing seasons.

Given a moderate climate, outdoor living is the ideal budgetary, energy-conserving, and usually most healthful choice that can be made depending on air pollution, noise, or other negative conditions. Walls, fences, earth berming, landscaping, and the configurations and attributes of architecture as well as the choice of paving, lawn, or other exterior surfaces can make outdoor spaces more habitable throughout the seasons of the year. Daily and seasonal solar positions and wind patterns should be primary design considerations, dictating the design, choice of materials, and location of the outdoor space.

SPECIALIZED MIGRATIONAL DESTINATIONS

Retreat Spaces

As adverse situations may arise, it is well to have a space or spaces within a home in which one can find protection. Such spaces can shield against or lessen the degree of harm or discomfort from high winds, cold, heat, air pollution, blackouts, earthquake, radioactive fallout, noise, intruders, or floods. Indirect rather than direct lighting is generally preferable for these areas. Active and hybrid solar systems and photovoltaics are more likely than passive systems to predominate as design elements for spaces remote from glazed areas.

Underground spaces can usually offer the most economic protection against high winds, cold, heat, and radioactive fallout. Earth coupling can stabilize the temperature and livability of an indoor retreat space. External noise is diminished by thermal mass. The potential for flooding requires elevated construction and an upper level means of escape. When outdoor air pollution is a problem, it is advisable to have a retreat space with an efficient indoor filtered-air system.

Superinsulation and tight construction can provide isolation from the extremes of climate and make solar, air tempering, and other natural energies easier to control.

A person can have a private retreat within a dwelling or in an outdoor space, studio house, or other outbuilding. Creative endeavors are often best pursued in an isolated environment. By isolating

TH880 .054

PASSIVE SOLAR
JOURNAL

sound, one can avoid disturbing others. Nooks and crannies can serve as places to sit alone, read, or convalesce. Meditation, sleeping, and resting can be enjoyed within a quiet isolated retreat space.

Rooftops

Usually overlooked as migrational destinations are rooftop spaces outdoors, quasi-indoors, or a penthouse. A roof can be a good retreat space for isolated endeavors or a place for entertainment; depending on microclimatic seasonal change, a roof can provide an ideal daylight, solar, and panoramic opportunity.

Outbuildings

Solar- and climate-responsive studio houses, gazebos, and outbuildings add a dimension to migration that extends outside the structure itself to the surrounding site.

CASE STUDIES

For more than 40 years the migrational experience with a solar, natural energy focus has been germane within a holistic planning and design context in projects I have done. An awareness of daily and seasonal migration has prevailed as a concern in conjuction with function, form, and aesthetics. The following case studies exemplify this approach.

Studio Passive Solar Residence (1955)

Project Description

This passive home is in an older, urban, upper-crust Denver, Colo., neighborhood (Figures 1 and 2). The west-facing hillside frontage is 50 ft (15 m) long and 125 ft (38 m) deep. On the south side, a solar patio courtyard made of aggregate concrete is inset within the architecture. Greenery on the perimeter and mist spray heads provide summer cooling. The front entrance patio to the street is bermed, and heavy landscaping lends privacy.

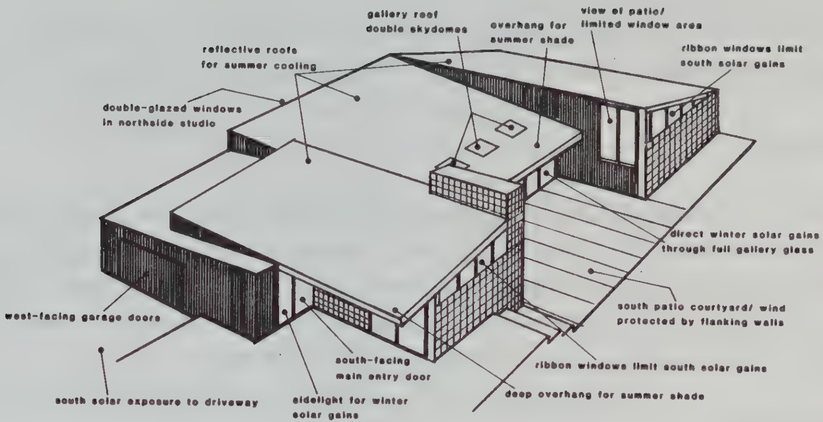


Figure 1. 1955 studio passive solar residence

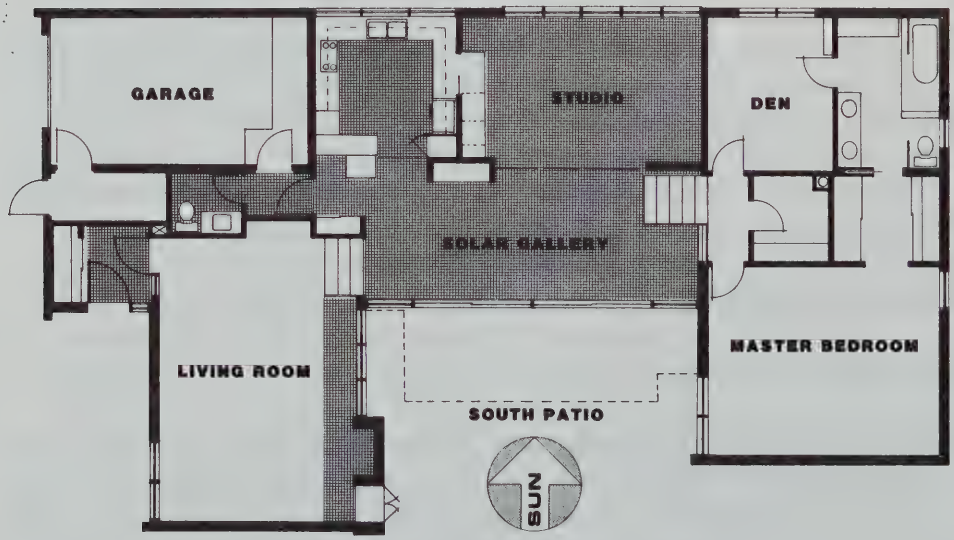


Figure 2. Studio residence, floor plan

The main floor, measuring 545 ft^2 (51 m^2), is at grade. The living room is used as a music room and is carpeted for acoustics. The room is daylit via windows overlooking the south patio courtyard. These windows provide the principal view as well; the view to the west is limited. Ribbon windows to the south limit solar gain and prevent direct radiation from entering the grand piano area in this room. West windows allow a limited view to the west patio shaded by trees and a deep roof overhang. An airlocked vestibule entry with south sidelight glazing benefits from direct passive solar gain in the winter. The fireplace is fitted with a special flue closure to avoid interior energy loss. Large masonry mass enhances indoor temperature stabilization.

The central split level is 672 ft^2 (62 m^2). The central indoor and outdoor patio courtyard is depressed into grade and earth coupled; this area receives optimal passive solar gains in the winter. Dark tile covers the concrete floor of the gallery and the kitchen, which is open to the area, and adjoining sculpture studio. Double-glazed studio windows provide north skyvault daylighting. High and wide side-sliding shoji panels admit north-side daylight and south-side thermal radiation and light. The shojis provide privacy as desired to the spacious studio.

In the rear raised level [720 ft^2 (68 m^2)] a small den that doubles as a guest bedroom and a large master bedroom overlook the patio courtyard. The upper bedroom level is segregated from the living areas at the rear of the site, away from disturbances and elevated above the courtyard. The south ribbon glazing prevents overheating of the raised master bedroom. North glazing for the den/bedroom is limited, but adequate for skyvault daylight and view.

The north side of the garage provides a cold weather buffer; the west-side garage doors face the street. The driveway is not shaded, so it receives direct solar radiation to hasten melting of snow and ice. An airlock passage separates the garage and the gallery, thus preventing fumes from entering the gallery and thermal loss to the outside.

The house is not air conditioned. Natural cross ventilation occurs by means of low intakes and high exhaust. Shade from dense landscaping and evaporative cooling from misting also help cool the house in hot weather.

A hydronic-zoned, gas-fired system provides heating, with below-body-temperature radiant slabs in the gallery and studio. The house is equipped with a gas-fired domestic hot water tank.

Results

The artist and her musician partner find the dwelling to be ideal for the cultural activities of art, sculpture, and music. Post-and-beam construction aid interior acoustics. They use the home for entertaining, music performance, and exhibiting sculpture within the gallery, studio, and patio courtyard. Only the raised bedroom wing is isolated from general activity. The openness of the home projects a sense of light and scale much beyond that of the physical dimensions of the architecture. The house is a stimulating setting for creative esthetic endeavors, with minimal energy demand, maximum functional use, and minimum maintenance. For its relatively small size, the house offers varied migrational experiences within and between interior and exterior spaces.

Outdoor Migrational Destinations

- South patio courtyard - sitting, sunbathing, relaxing, eating, conversing, entertaining, playing music, exhibiting sculpture.
- West entry patio - receiving visitors, gathering, intermission space.

Indoor Migrational Destinations

- South Thermal Zone
  - Living room (main level, limited direct gain) - socializing, reading, conversing, practicing and performing music.
  - Gallery (central level, direct gain) - dining, entertaining, gathering to listen to music, sunbathing, exercising, exhibiting sculpture.
  - Master bedroom (raised level, limited direct gain) - resting, meditating, sleeping, reading, watching TV.

- North Thermal Zone
  - Kitchen (central level) - preparing food, cooking, eating.
  - Studio (central level) - sculpting, artwork, exhibiting sculptures, gathering.
  - Den/bedroom (raised level) - writing, reading, office work, resting, sleeping.

Crowther Passive Solar Residence (1961)

Project Description

This home is in an older parkway neighborhood in Denver, Colo. (Figures 3-5). The south-facing street frontage measures 50 ft (15 m) by 130 ft (40 m). A south-facing, brick-paved solar courtyard is walled and surrounded with low evergreens for privacy. Summer cooling is provided by mist head sprays and landscaping of a deep vegetative mat (*Vinca major*) on the front berm.

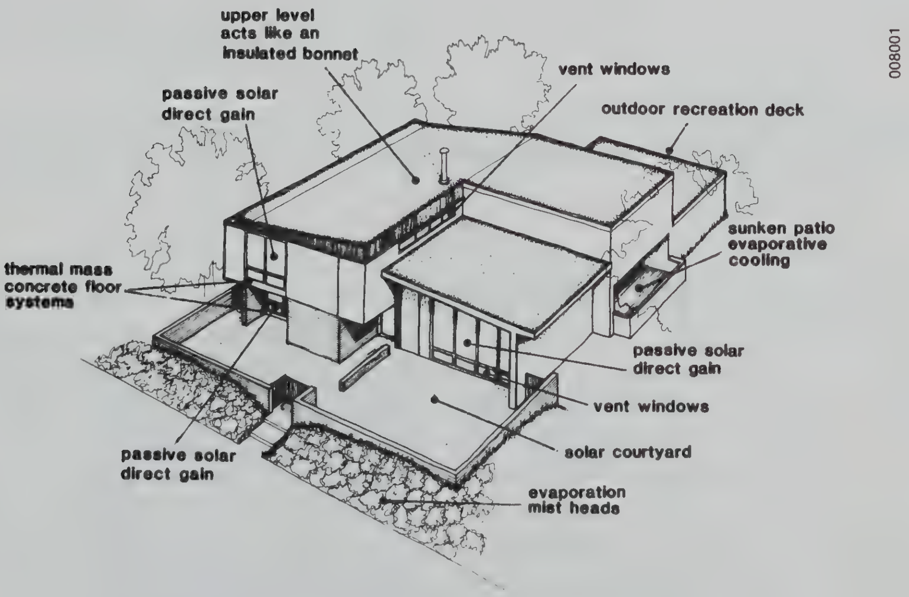

upper level acts like an insulated bonnet
vent windows
passive solar direct gain
outdoor recreation deck
sunken patio evaporative cooling
thermal mass concrete floor systems
passive solar direct gain
vent windows
solar courtyard
passive solar direct gain
evaporation mist heads
008001

Figure 3. 1961 Crowther passive solar residence

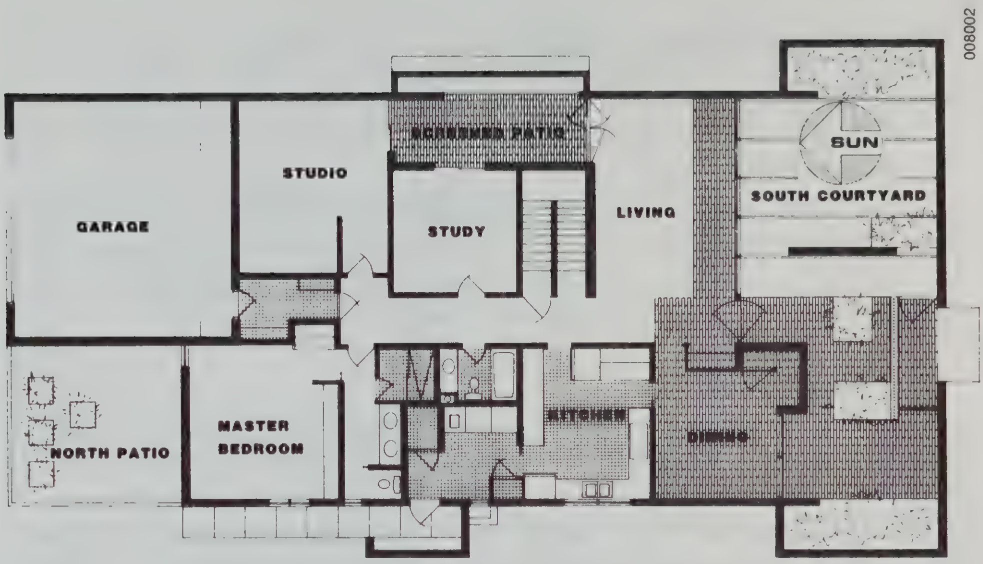


Figure 4. Crowther residence, main level floor plan with thermal mass areas

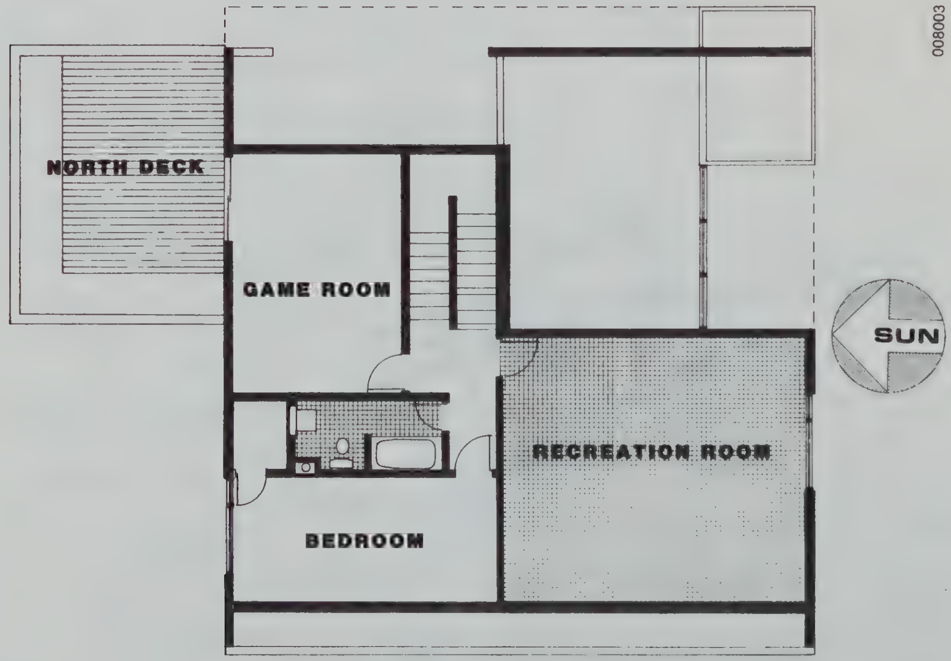


Figure 5. Crowther residence, upper level floor plan

The principal living quarters are on the main floor and occupy 1730 ft^2 (105 m^2). This area is designed for optimal passive solar gains from the south in the winter and is architecturally shaded in the summer. The main floor is set 3 ft (1 m) into grade and is earth coupled. Construction is slab on grade with dark brick floors; the east and west have exterior cavity insulated brick walls. Principal glazing is to the south and to the east toward the sunken screened patio; there is limited glazing to the west and north. A skylight illuminates the stairway.

The basement doubles as a fallout shelter. Construction of the basement is concrete floor slab with heavy structural concrete ceiling and earth-protected concrete foundation walls. The basement is air vented and has an escape hatch.

The second floor [1130 ft^2 (105 m^2)] is designed to be entirely closed off from the main floor. It is ideal for family gatherings, guest quarters, and other special uses and activities. The front upper level is passively heated. This area has a prestressed concrete floor system. The roof and upper level exterior frame walls are well insulated. Glazing on this floor is principally to the south, with limited glazing to the east, west, and north.

Baseboard heating is provided by a gas-fired zoned hydronic system. The heating units are in the partial basement next to the fallout shelter.

The house is not air conditioned. A row of screened awning windows on the south of the main floor are primary ventilation intakes. Interior air is exhausted from upper level ribbon windows to the east and above the upper stairway. All interior spaces benefit from cross ventilation. The central main floor has a brick wall that helps moderate interior temperatures. The front entry area is cooled by mist sprays on the front landscaped berm. The front door is louvered to permit ventilation from the cooled entry area. A gravel trough on the sunken screened patio on the east provides evaporative cooling of the patio and the main floor living room, study, and studio that open directly onto the patio. Food storage space in the house is earth cooled.

Results

The main level stays cool during summer's hottest days. The upper level stays reasonably comfortable, being cooled by nocturnal air and closed off during the day. The many zones of the hydronic baseboard system with thermostats in each room result in minimal heating demand. Comfortable, diverse use of space and conservation of energy are possible throughout the seasons because of several architectural features: the upper-level, insulated architectural "bonnet" superimposed over the main level, which consists of a large thermal mass of exterior and interior brick walls on a thermal concrete floor; the coupling of this level to the earth below the frost line; and the prestressed concrete mass between the main and second floors.

Migration to the levels of the house follow the sun and conditions of the climate. The outdoor courtyard is habitable on sunny days in cold weather. The patio and upper deck on the north side are used during spring and fall days and summer nights.

The sunken screened east patio on the main floor is used for most meals and snacks during the summer as well as for relaxing and more stimulating activities during spring, summer, and fall. The two floor-level and outdoor spaces are conducive to diverse uses, particularly for enjoying the natural surroundings. This is truly a migrational house, with movement along the long main central corridor (used for wintertime running) and the destinations suited to many functions and states of mind.

Outdoor Migrational Destinations

- South courtyard - sunbathing, eating, gardening, entertaining.
- North deck (upper floor) - entertaining, recreation.

Indoor Migrational Destinations

- South Thermal Zone
    - Living room (direct gain) - reading, watching TV, conversing, sunbathing.
    - Dining room (direct gain) - dining, writing, conversing.

  - Recreation room (upper floor/direct gain) - relaxing, entertaining, family gathering, art and photo display, visual projection, games, dancing, guest quarters, children's playing, exercising, photography, solar food drying.

- Central Thermal Zone
  - Basement fallout shelter - storage of food supply and shelter provisions; hot water tanks; thermal, storm, and fallout retreat space.
  - Stairway (ventilation cooling) - exercising.

- East Thermal Zone
  - Study - home office, message center, writing, reading, relaxing, daytime naps, meditating.
  - Studio (earth coupled) - designing, drafting, writing, artwork, reading, practicing or listening to music, playing, composing.
  - Screened patio (evaporative surface cooling) - sitting, relaxing, conversing, reading, clothes drying, airing bedding.

- West Thermal Zone
  - Kitchen (earth coupled) - preparing food, cooking, eating.
  - Bedroom (upper floor) - solitude, meditating, guest sleeping, retreat from noise and activity.

- North Thermal Zone
  - Master bedroom (earth coupled) - sleeping, resting, exercising, grooming.
  - Master bedroom patio (open to the sky) - sitting, exercising, resting, privacy.
  - Game room (upper floor) - pool playing, socializing.

Highline Canal Residence (1981)

Project Description

The site for this house (Figures 6-9) is a clearing on a large urban wooded area along the Highline Canal in Denver, Colo. The house has full solar exposure, with a south-facing, concrete-paved patio running the width of the home. A wooded area acts as a windbreak to cold north and northwest winds.

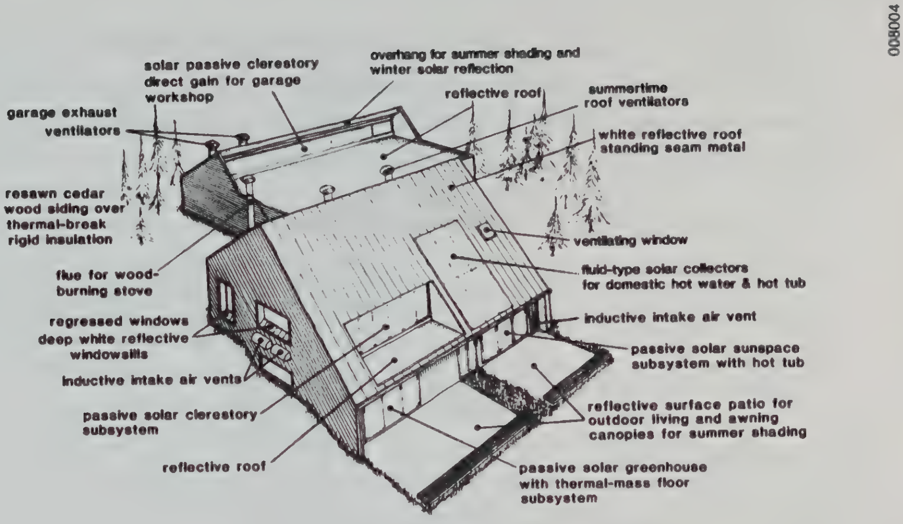

008004
solar passive clerestory direct gain for garage workshop
overhang for summer shading and winter solar reflection
reflective roof
summertime roof ventilators
garage exhaust ventilators
white reflective roof standing seam metal
resawn cedar wood siding over thermal-break rigid insulation
ventilating window
flue for wood-burning stove
fluid-type solar collectors for domestic hot water & hot tub
inductive intake air vent
regressed windows deep white reflective windowsills
passive solar sunspace subsystem with hot tub
inductive intake air vents
reflective surface patio for outdoor living and awning canopies for summer shading
passive solar clerestory subsystem
reflective roof
passive solar greenhouse with thermal-mass floor subsystem

Figure 6. 1981 Highline Canal residence

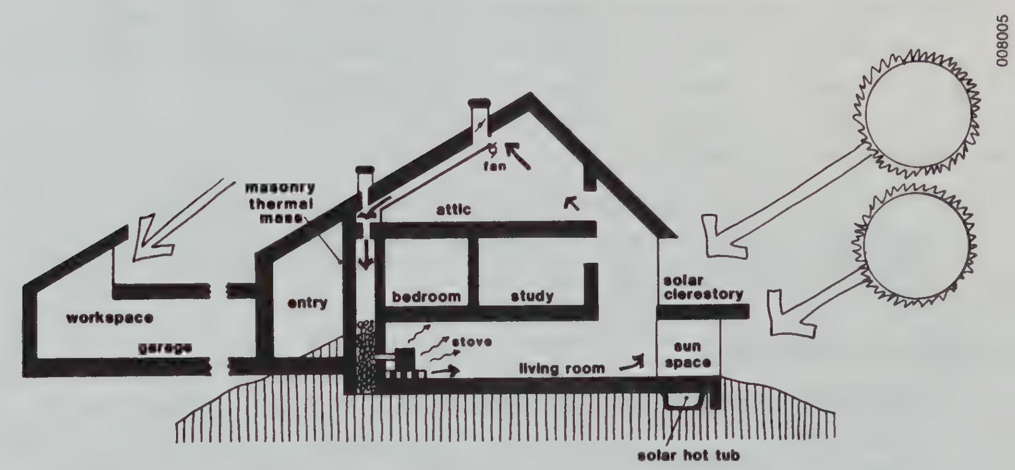


Figure 7. Highline Canal residence, section

The main floor [1700 ft^2 (158 m^2)] is earth sheltered with a double-envelope masonry thermal mass wall on the north side filled with gravel and insulated on the exterior. An unheated airlocked entry is on the east side. The house has two sunspaces; one on the southwest adjoins the dining-living space and a second fully glazed southeast-facing one containing a hot tub is off the master bedroom. The floors of both sunspaces are concrete overlaid with dark tile. Overhangs provide shade in the late spring, summer, and early fall.

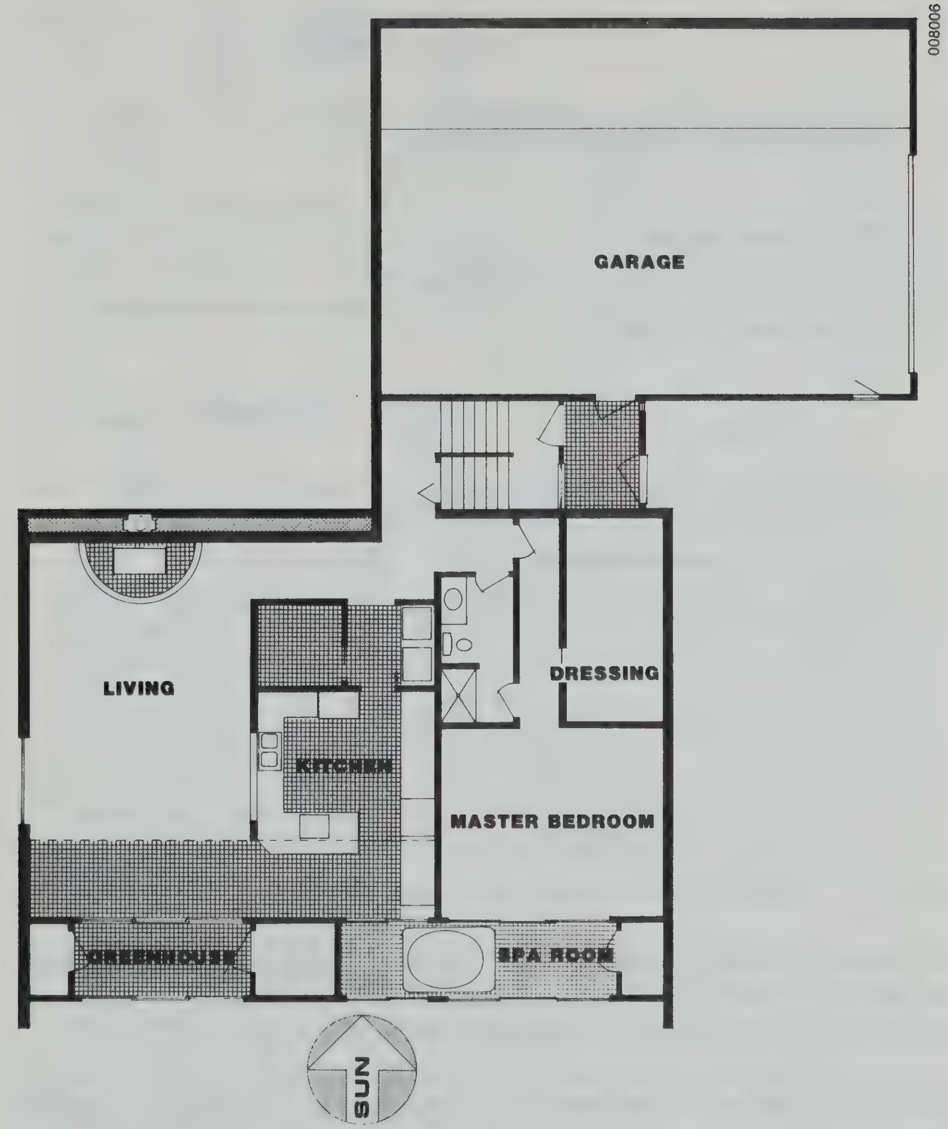


Figure 8. Highline Canal residence, main level floor plan

The house has limited glazing to the east and the west and none to the north.

Heat collected from direct and indirect gains from the main and upper-level south glazing rises to the attic. There, a thermostatically operated blower delivers the hot air into the north-facing, masonry, thermal-mass cavity wall. Heated air is forced through

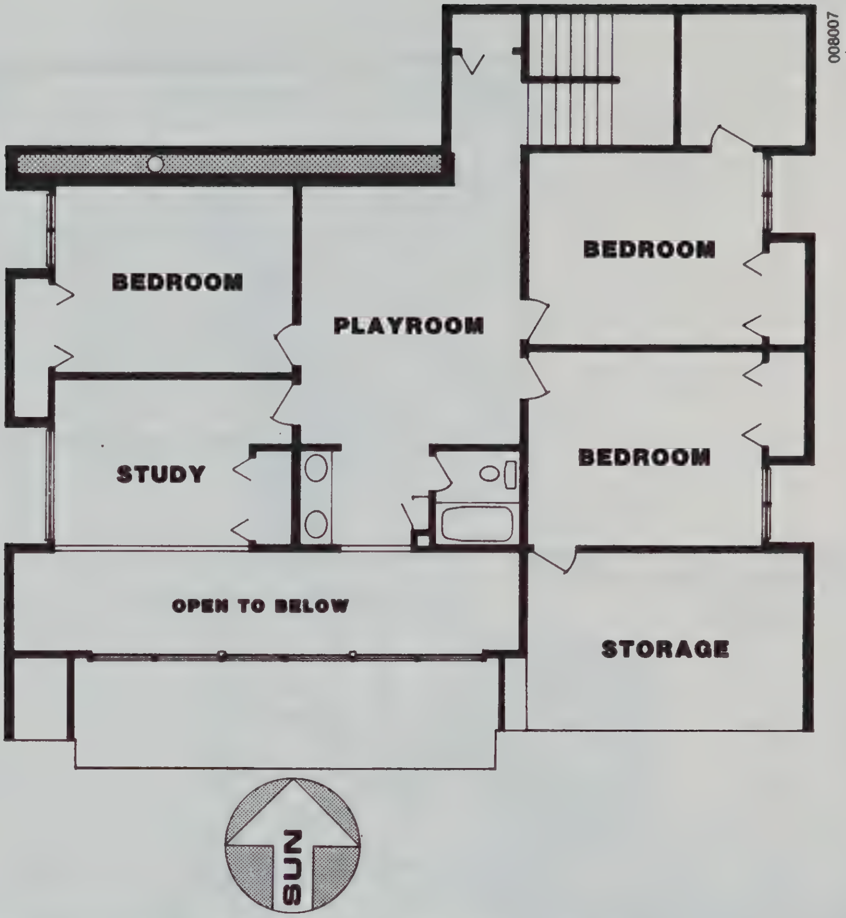


Figure 9. Highline Canal residence, upper level floor plan

the gravel-fill cavity where interior relief vents distribute residual heated air to the lowest level. A high-efficiency wood stove can add heat to the thermal mass wall on the north side.

The garage and workshop area measures 1050 ft^2 (98 m^2). A passive solar clerestory provides light and thermal gains to the workshop, which is used primarily for restoring classic cars. The thermal mass north wall receives direct wintertime solar radiation. A clerestory provides shade in the summer. The reflective roof augments daylighting and thermal radiation.

The second floor, measuring 1500 ft^2 (139 m^2), is topped with a superinsulated roof. The upper-level clerestory windows are recessed for summer shading but have a reflective ledge that enhances solar gains in the winter. The upper level is open to the lower level and includes a children's play space flanked by bedrooms.

The house is not air conditioned. Electric hydronic baseboard units with multizoning provide backup heat as needed to individual rooms.

Ventilation and air tempering are provided by south sunspace patio doors. There are wind turbine ventilators on the roof ridge and garage. The principal roof is white ribbed metal to reflect summer solar radiation. The attic fan can be ducted to the outside for convective heat exhaust in warm weather, or night air can be directed into the thermal mass cavity wall for earth-coupled hybrid system cooling.

Results

With the wooded privacy and large outdoor open space to the south, this house can accommodate migrational sports activities. People can enter spacious outdoor patios through the sunspaces from the living room, kitchen, and master bedroom. The house is ideal for an active family with children because the children in the second floor play area can be heard on the main level. All interior spaces, including those of the garage as a workshop and repository of vintage cars, optimize migrational pathways and flexibility in space use. Daylighting and direct solar radiation are carefully controlled to maximize internal seasonal illumination according to functional use. The owners comment that every inch of the house is used in many ways.

Outdoor Migrational Destinations

- Outdoor lawn areas - volleyball, football, soccer, baseball.
- South patios - sunbathing, eating, gardening, entertaining, socializing, exercising, playing, dancing.
- Wooded area - picnicking, playing, observing nature.

Indoor Migrational Destinations

- South Thermal Zone
    - Living room (earth-coupled, thermal mass hybrid solar) - entertaining, family gatherings, reading, watching TV, conversing.

  - Dining area (as extension of the living room; earth coupled, secondary gain) - dining, entertaining, writing, study, conversing, extension of activities into sunspace.
  - Kitchen (secondary gain) - informal eating, preparing food, cooking, writing.
  - Master bedroom (earth coupled, secondary gain) - sleeping, resting, reading, writing, sunbathing and using spa in sunspace.

- Central Thermal Zone
  - Play area (second floor, daylight and direct solar radiation) - playing, exercising, games, family activities.
  - Bedrooms (second floor, east and west glazing) - resting, sleeping, playing, guest rooms.
  - Attic space - access for playing, games, rope climbing.

- North Thermal Zone
  - Garage/workshop - restoring and adjusting antique cars, periodic entertaining.

Deerfield Solar Residence (1985)

Project Description

The house is on a 5-acre (2-ha) south-sloping rural site 30 miles (48 km) southeast of Denver, Colo. (Figures 10-14). It sits on a knoll

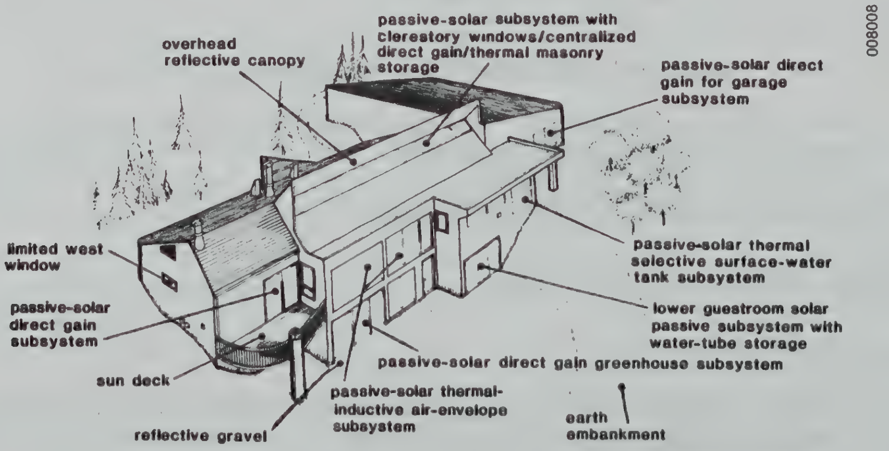

passive-solar subsystem with clerestory windows/centralized direct gain/thermal masonry storage
overhead reflective canopy
passive-solar direct gain for garage subsystem
008008
limited west window
passive-solar thermal selective surface-water tank subsystem
passive-solar direct gain subsystem
lower guestroom solar passive subsystem with water-tube storage
sun deck
passive-solar direct gain greenhouse subsystem
passive-solar thermal-inductive air-envelope subsystem
earth embankment
reflective gravel

Figure 10. 1985 Deerfield solar residence

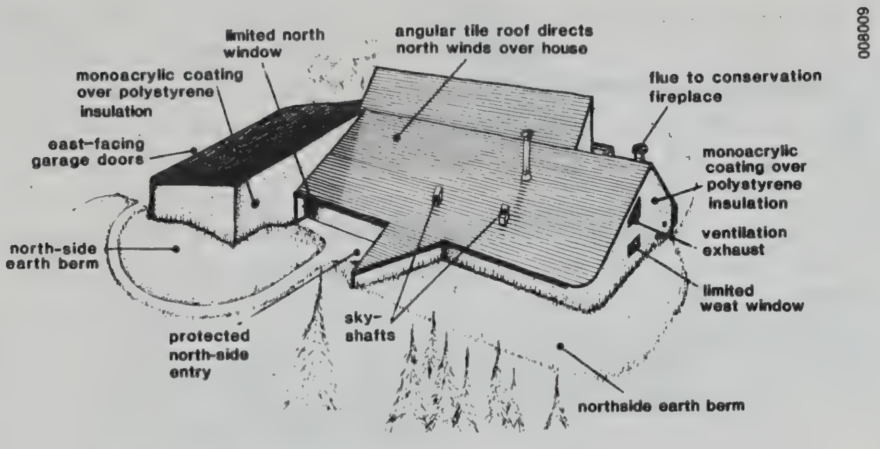

limited north window
angular tile roof directs north winds over house
monoacrylic coating over polystyrene insulation
east-facing garage doors
flue to conservation fireplace
monoacrylic coating over polystyrene insulation
ventilation exhaust
north-side earth berm
limited west window
sky-shafts
protected north-side entry
northside earth berm
008009

Figure 11. Deerfield residence, view from northeast

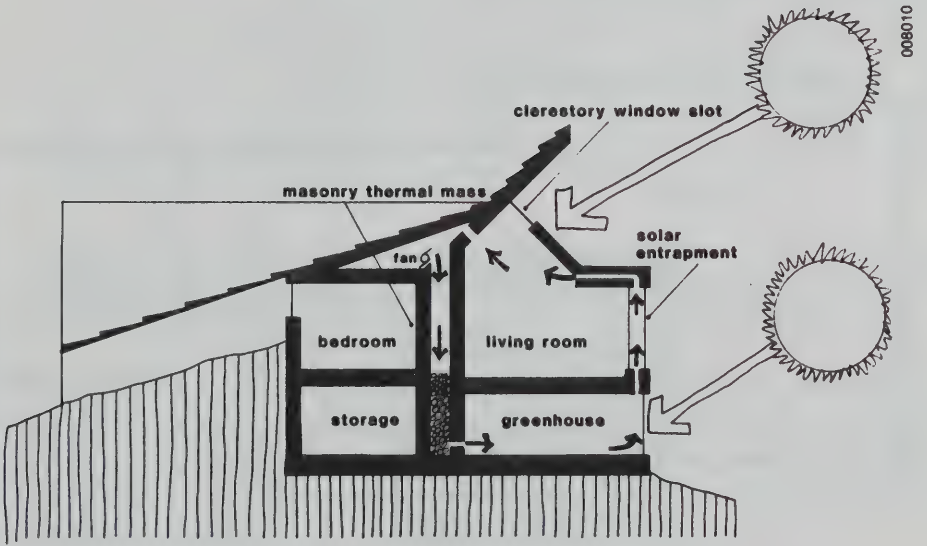


Figure 12. Deerfield residence, section

at an elevation of 6500 ft (1981 m) with a panoramic view of the Rocky Mountains uninterrupted to the southwest, west, and northwest. Views are significant in this house; carefully planned fenestration encourages the observing of mountains, a forest on an opposite ridge, south slopes stretching below, and the wildlife and birds. The house has a due south orientation with no solar occlusion. On the south side is a large wind-protected patio; on the

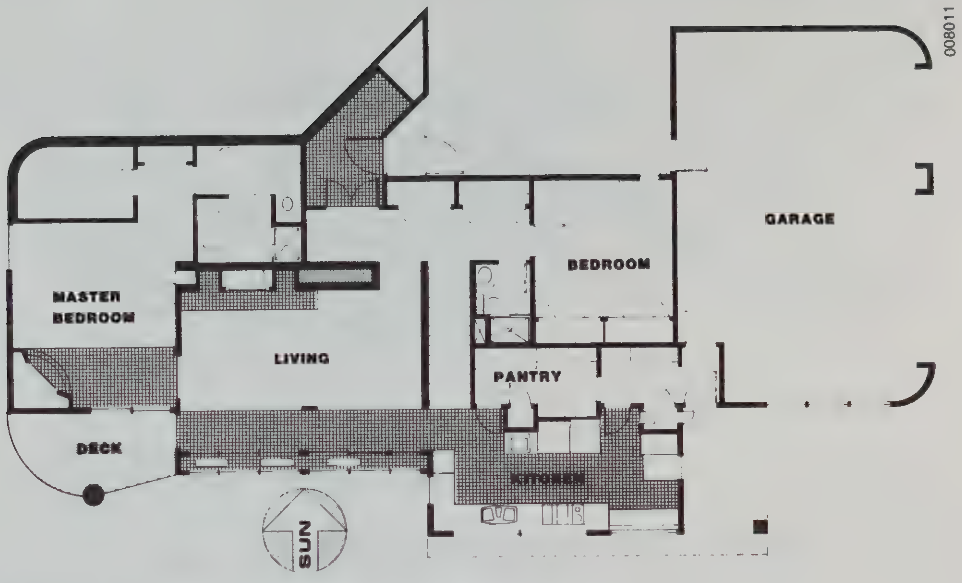


Figure 13. Deerfield residence, main level floor plan

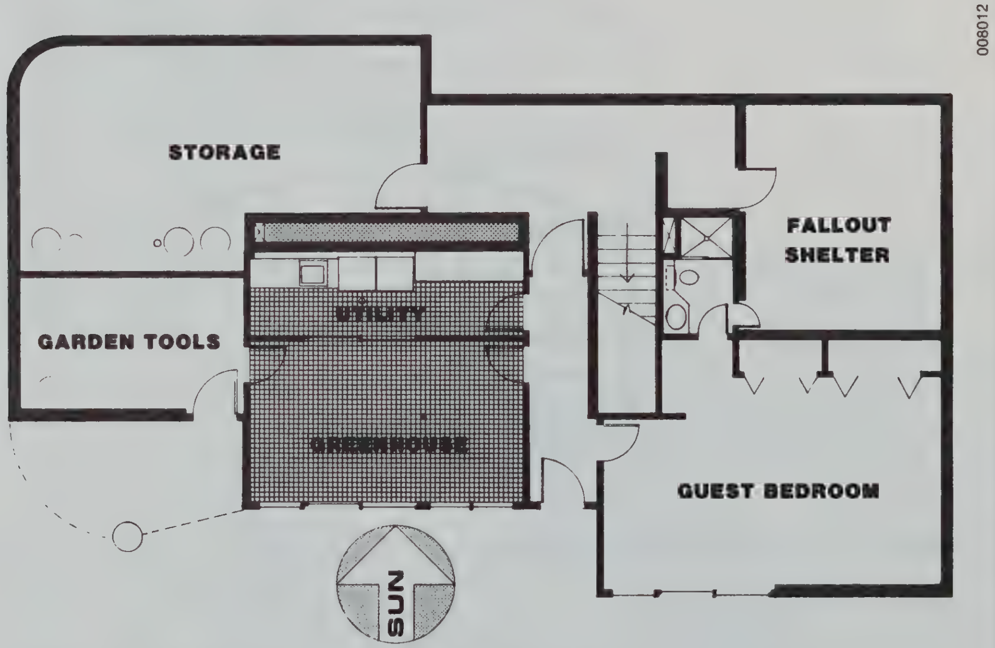


Figure 14. Deerfield residence, lower level floor plan

southeast, a patio porch. The north-sloping roof aligned with the north-sloping earth berm divert the cold north wind over the heavily insulated attic space.

There is optimal passive solar exposure to the principal living areas on the main floor [1900 ft^2 (177 m^2)] in winter. The south sunspace shades this level in summer, but introduces direct gain heat into the main floor in winter. This heat is driven with a thermostatically controlled blower into the vertical gravel-filled cavity of a large central double-walled thermal mass. An energy-conserving, heat exchange fireplace with glass doors is also built into this mass wall. A south-facing clerestory contributes to the collection of heat in the central thermal mass and north-side spaces. The breakfast area contains eutectic salt storage that receives direct winter solar gains. Direct gain and natural ventilation are provided to the master bedroom through patio doors leading to an outside deck. To the east is an airlock entry.

The lower level, measuring 1860 ft^2 (173 m^2), is earth sheltered and earth coupled. A large solar greenhouse is on the south side. Heated air from the greenhouse passes into the main floor sunspace through floor registers. The guest room is heated with passive solar. The house plan includes a fallout shelter retreat space. A domestic hot water tank is accessible to the fallout shelter. On the north side of the house is a large earth-coupled storage area.

The home is heated by electric hydronic baseboard heating with separate room thermostats. Domestic hot water is provided with a solar drain-back system.

The house is cooled by means of natural ventilation through three levels. A large louvered vent in the lower-level greenhouse admits ventilation air. Air is exhausted at the attic ridge. Nighttime ventilation may be supplemented with a fan-powered, filtered air system.

Results

The occupants of the home consider its design to be both stimulating and calming; they find particular relief from their workplace stresses and say that weekends seem like holidays. They delight in the interplay between the architecture and the views and sounds of the natural surroundings.

The large expanse of glazing in the lower and main levels and clerestories optimizes winter sunlight and thermal gains, the living rooms being especially luminous. The north-side bedrooms are more secluded and receive only a portion of the solar radiation. These areas become pleasant daytime retreats.

Outdoor Migrational Destinations

- South patio (lower level) - sunbathing, gardening, entertaining.
- South porch patio (main floor) - sunbathing, observing nature, eating, conversing, relaxing, exercising.

Indoor Migrational Destinations

- South Thermal Zone
  - Living room (hybrid-passive solar sunspace) - socializing, reading, conversing, relaxing, observing nature.
  - Dining room (hybrid-passive solar sunspace) - dining, socializing, writing, conversing.
  - Master bedroom (direct gain) - sitting, relaxing, studying, observing nature (also from outdoor deck).
  - Kitchen (direct gain) - preparing food, cooking, observing nature.
  - Breakfast nook (direct gain, eutectic salts storage) - eating, conversing, reading, writing, observing nature.
  - Greenhouse (lower level, direct gain) - growing food and decorative plants, drying clothes, sunbathing in winter.
  - Guest room (lower level, direct gain) - guests, retreat space, special tasks and activities, resting, meditating, sleeping.
  - Garage (direct gain) - storing four cars, workspace.
- North Thermal Zone
  - Main entry - airlocked, transition vestibule between outdoors and indoors, unheated.
  - Bedroom (clerestory direct gain) - relaxing, mediating, writing, reading, sleeping, observing sky.
  - Storeroom (lower level) - storage, retreat space.
  - Fallout shelter - food storage, shelter provisions, thermal storm and fallout shelter retreat space.

CONCLUSION

These case studies exemplify the significance of migration pathways as a central theme of climate-responsive architecture. We clearly benefit from exercising a holistic sensitivity in our approach to the conception, planning, and design of a site and its surroundings. The benefits are far-reaching: as we localize and shorten our lines of migration, we lessen the use of the world's polluting fossil-fuel energies. Living with the sun and the forces and moods of the natural climate and the earth is a vitalizing experience within the migrational province of architecture. The critical relationship between design and nature is addressed by Richard Neutra in *Survival Through Design*:

> "We must still design living space, and a current environment...so that the neurologically salubrious agents of nature outside are freely admitted and kept active to as great an extent as possible.
>
> "The farther man has moved away from the balanced integration of nature, the more his physical environment has become harmful.
>
> "It becomes improbable that a species like ours, wildly experimenting with its vital surroundings, can persist."

Passive Solar Journal, 4(2), 171-186 (1987)

Solar Access in Boulder, Colorado

Peter Pollock
Department of Community Planning and Development
City of Boulder
P.O. Box 791
Boulder, Colorado 80306

Abstract

There are a variety of approaches to solar access protection, including solar easements, restrictive covenants, and land use planning techniques. Boulder, Colo., enacted a solar access ordinance in 1982 that uses site plan review to encourage solar siting and the use of a solar "fence" to protect solar access. Five years later four lessons are clear: 1) solar access protection for the south walls of houses sited on north-south streets is difficult to achieve, 2) requiring east-west building orientation in new developments without solar access is meaningless and better results may be achieved through a performance-based approach, 3) solar access permits have not been used in the numbers anticipated as a way to increase solar access over and above the protection *of the solar fence, and 4) residential and commercial buildings should not be treated the same for purposes of solar access and siting.*

INTRODUCTION

In covering President Jimmy Carter's address to the nation in July 1979 on the energy crisis, the *New York Times* reported that someone told the President "when we enter the moral equivalent of war, don't issue us BB guns." Sentiments and conditions have changed dramatically. The immediate concerns over energy supply and price in the late 1970s that led federal, state, and local policy makers to pursue energy conservation and alternative energy programs have disappeared. To the extent that some energy conservation practices have been adopted and certain alternative energy products such as solar greenhouses and high efficiency furnaces have had consumer appeal, progress continues. But in terms of having solar water heaters on every rooftop, enthusiasm has died.

Local governments in the late 1970s and early 1980s were encouraged by federal and state governments to examine their city planning practices and amend their land use regulations to encourage energy-conserving land use practices and alternative energy technologies. Land use regulations can restrict the use of solar energy. Building height restrictions can limit the addition of solar collectors to rooftops, and building setback requirements can prohibit solar greenhouse additions to existing houses. Many local governments refined definitions and added exception procedures to clear the way for new solar technologies.

Beyond removing existing barriers, city planners were encouraged to focus on two new areas: 1) the review of new developments to ensure that they embodied the latest notions of energy-efficient design, and 2) the protection of solar access within existing developments. For new developments the goal was to provide for as much solar access as possible during the initial design and construction of buildings and to site new buildings to allow incorporation of passive and active solar technologies. Within existing developments, the goal was to develop a way to protect existing levels of solar access and to provide solar access to what few solar systems had already been added to existing buildings.

With all this encouragement, why don't more towns have solar access ordinances? Not all citizens feel that local governments should exercise a role in these areas. In communities such as Boulder, where a sophisticated system of land use regulation is the norm, the addition of solar access controls was not considered unusual. To require the consideration of building and street location in order to enhance solar access in new development presupposes that a local government reviews site plans. Many towns would just as soon publish a list of lot size requirements, building setbacks, and street and utility standards and issue building permits. A planned unit development process where there is flexibility in site design standards requires a reviewer, a review process, and a review board. Some towns would rather not bother with this process. Even if a city does have this process, solar access may not be considered significant enough to justify the increased staff or developer time to document. When Boulder was considering its solar access ordinance, the development community argued that market forces would be sufficient to dictate energy-conserving site design and that consumers would demand this site plan feature if it were truly needed.

OPTIONS FOR SOLAR ACCESS PROTECTION

Local government regulation is not the only way to provide solar access protection within existing areas. If I plan a solar greenhouse for my home, I can negotiate a solar easement with my neighbor to the south. A solar easement would restrict my neighbor from building any structure that would shade my solar system during critical times. Exchanging a symbolic dollar and recording an agreement against the property is sufficient to guarantee solar access. Many states passed enabling legislation to clear the way for the creation of such solar easements. Local governments can provide model documents to property owners and assist in recording them. Such easements typically "run with the land," thus remaining effective through changes in property ownership or changes in use.

So what is the problem? The use of solar easements for solar access protection has been criticized on three grounds:

1) An easement requires a legal description of the property that will be restricted by the easement. For a solar access easement this means a plane projected across your neighbor's property

defined by the lowest arc of the apparent path of the sun during critical solar gain periods. This defines a kind of skyspace within which your neighbor can build (Figure 1). The average homeowner does not have the expertise needed to provide this technically complex legal description.

008013

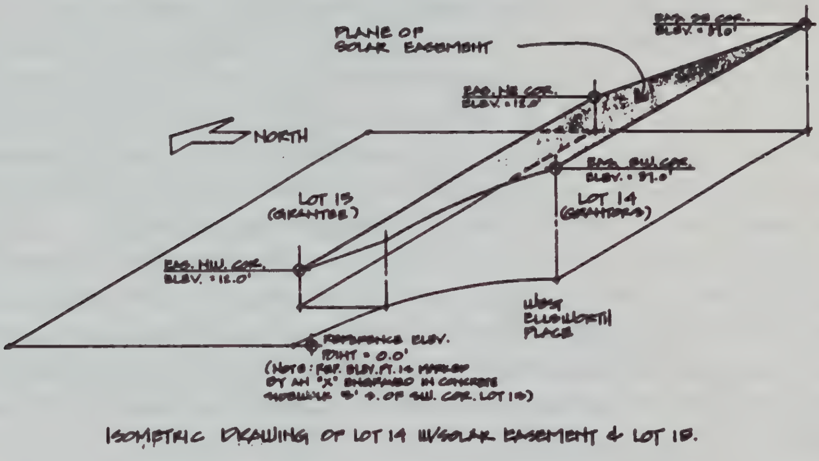


Figure 1. Example of the skyspace defined by a solar easement

2) While the law only requires a symbolic exchange of money, the actual costs may be much more. If my neighbor has visions of building an apartment, neighborhood grocery store, or simply a second floor addition, the avoided value of such redevelopment potential may be high. This transaction cost of solar development may leave most solar systems owners without any guaranteed solar access.

3) Before anyone undertakes negotiation of such an agreement, they have to be quite serious about wanting a solar system. This approach, therefore, leaves out everyone who is not interested in adding solar features now but would consider doing so in the future. If in the meantime a neighbor builds to the south of such a homeowner, what good is a nonexistent solar easement?

Other approaches have also been suggested. Restrictive covenants or deed restrictions of homeowners' associations can protect solar access within developments. This tool can ensure that solar access created through the initial site planning process can be preserved in the face of change, but it does not address existing neighborhoods without homeowners' associations. Enforceability is a concern because neighbors will not usually risk neighborhood disharmony over the issue of infringement of solar access.

Some advocated the use of a "prior appropriation, beneficial use doctrine" similar to that used in water law in the west: If you install and use a solar system before your neighbor builds an addition, you have effectively secured solar access. To a city planner this is too simple. For instance, if a city's zoning encourages a neighborhood shopping center at a particular location, the mere presence of a working solar collector on a neighboring structure could preclude a building of sufficient size. Cities generally want more control over the shape of urban development than this approach to solar access protection can provide.

Not surprisingly, city planners are most comfortable with using some variant of the building mass and bulk regulations present in every zoning code in the United States. Building setbacks and restrictions on building height create an envelope within which a building can be placed. Solar access brings a new dimension to the creation of a height restriction. Rather than just a vague notion of what constitutes buildings that are too massive, sun angles can define the limits precisely. And because building envelopes are different for different land use zones and densities, planners can use these existing distinctions to control the amount of solar access provided.

BOULDER'S SOLAR ACCESS ORDINANCE

Boulder, Colo., was one of 17 cities in the Comprehensive Community Energy Management Program funded by the U.S. Department of Energy. Being part of this program allowed planners in Boulder to perform an elaborate audit of energy use and supply in the community, run a large community participation process, create an action plan, and form an energy advisory board to begin revising the City's land use regulations. The City Council adopted a policy goal of zero energy growth. Solar site planning and the development of solar access protection within existing areas was part of that program.

Luke Danielson (1982) in his article, "Drafting a Solar Access Ordinance: One City's Experience," describes how Boulder crafted a solar access ordinance. Danielson points out the need for a diverse group of people to prepare such an ordinance, including builders, solar installers, a tree expert, and someone with a general knowledge of land use and zoning. Taking the concerns of many people into account was an important aspect of the success of Boulder's ordinance, but Danielson warns against seeking their participation before a well worked-out proposal is on the table.

The City of Boulder handles solar access as follows. When a raw piece of land is developed, the site plan is reviewed to ensure that buildings are sited so that the longer axis of the structure is oriented within 30° of a true east-west direction to maximize passive solar gain. In addition, 75 ft^2 (7 m^2) of solar collector area per residential unit must be provided on a rooftop that is either flat or oriented south. This provision was designed to allow for the future use of solar water heaters. Waiver provisions address topography and other factors outside the control of the developer. Exemptions were granted to everything built before the law passed. Exceptions are given for both unheated buildings and projects that use renewable energy systems or significant levels of energy conservation.

When an addition is proposed to a house, the building permit is reviewed to make sure that any property that could be shaded on 21 December between 10 a.m. and 2 p.m. is not shaded any more than a solar fence on their property line. A solar fence is an imaginary fence over which an adjacent structure cannot shade between the hours of 10 a.m. and 2 p.m. on 21 December. The height of that fence depends on the land use zone of the property. If your house is in a single-family neighborhood, that fence is 12 ft (4 m) high. If you have a condominium or apartment building in a medium- or high-density neighborhood, that fence height is 25 ft (8 m). A 12-ft solar fence in a low-density zone allows for solar access to the south wall of a structure when building lots are oriented north-south. This is due to a required 25-ft front yard and rear yard setback. The shadow length of a 12-ft solar fence at noon on 21 December is 24 ft (7 m) at Boulder's latitude. The 25-ft solar fence requirement in medium- and high-density residential zones is designed to provide solar access to the rooftops of these structures. In low-rise Boulder, 25 ft is a typical building height.

There are a variety of exclusions, exemptions, and exceptions to the solar access ordinance. If you are a business owner you probably do not have a solar fence protecting your property. This is partly because of the principal goal of reducing energy consumption for the residential sector and partly because of the feeling that commercial interests can better rely on private approaches to solar access protection. When the Flatirons, part of the Rocky Mountain foothills, shade a house more than a proposed house addition, an exemption can be granted. Exceptions are reviewed by the Board of Zoning Adjustment if the shading exceeds the solar fence. City staff can grant the exception if the affected property owner does not object and solar potential is not significantly reduced.

Solar users who live in neighborhoods that were developed before the passage of the solar access ordinance or who want more solar access protection than the solar fence provides can apply for a solar access permit. The permit defines a solar fence height and other restrictions such as the planting of trees. This permit is like a solar easement, but with one important distinction: it can be granted over the wishes of the affected property owner. The Board of Zoning Adjustment considers the energy-conserving potential of the solar energy system to be protected and the effect of the solar fence restrictions on the affected property owner. Even if the affected property owner objects, the Board can provide for increased solar access protection.

EXPERIENCE WITH THE BOULDER ORDINANCE

In the past five years we have reviewed hundreds of new developments and building permits. The planning staff and the Board of Zoning Adjustment have had to continually redefine the goals of the program and set new policy for specific cases. In one case, the owners of already finished solar homes wanted solar access permits to prevent a developer from building higher single-family homes in the area. In another case, an absentee landowner illegally built a deck that shaded a vacant lot down a steep north-facing slope. In the first example solar access permits were issued when it appeared that the restrictions would not limit the developer to single-story houses. In the other case, the owner of the illegal deck had to remove and redesign the deck, and solar access was protected for a future building site.

What lessons have been learned?

With all these experiences, we have learned several important lessons. One is that existing houses on north-south running streets are a problem. Usually there are just 10-15-ft (3-4.5-m) sideyard setbacks to separate homes. At 40° north latitude, a 12-ft solar fence casts a shadow 24 ft (7.3 m) long at noon. Through the review of several such cases before the Board of Zoning Adjustment, a consistent policy has been developed; because the siting characteristics of single-family houses on north-south streets effectively removes the south wall solar potential of shaded buildings, a solar exception can be granted if adequate rooftop area is shade free.

A typical case is shown in Figures 2-7. The first drawing shows the elevation from the street and the location of the shadow of the 12-ft solar fence shadow on the south side of the building. Figure 3 indicates the point on the house where the actual shadow from the proposed house at 3165 10th Street would hit. This demonstrates that the proposed house shades more than the 12-ft solar fence. An exception is therefore required. Figures 4 and 5 compare the solar fence shadow and the actual shadow from a plan view. Figures 6 and 7 show the impact of the solar fence shadow and actual shadow on the south elevation of 3175 10th Street. A solar exception was granted because 3175 10th Street had limited potential for a passive solar addition at ground level because of a driveway and sideyard setback requirements and the developer of 3165 10th Street had adjusted building mass to minimize shadowing.

A second lesson is that the solar siting requirement for new developments that arranges buildings with their longer axis within 30° of an east-west direction in land use zones with a 25-ft solar fence does not adequately allow passive solar potential. Boulder's low-density zone for developing areas encourages detached dwellings on 5000-6000-ft^2 (464-557-m^2) lots. If the building is oriented east-west, then the lot is oriented east-west and the streets run north and south. With a 25-ft solar fence and only sideyard setbacks separating buildings, there is not adequate solar access for ground-level solar energy systems.

008014

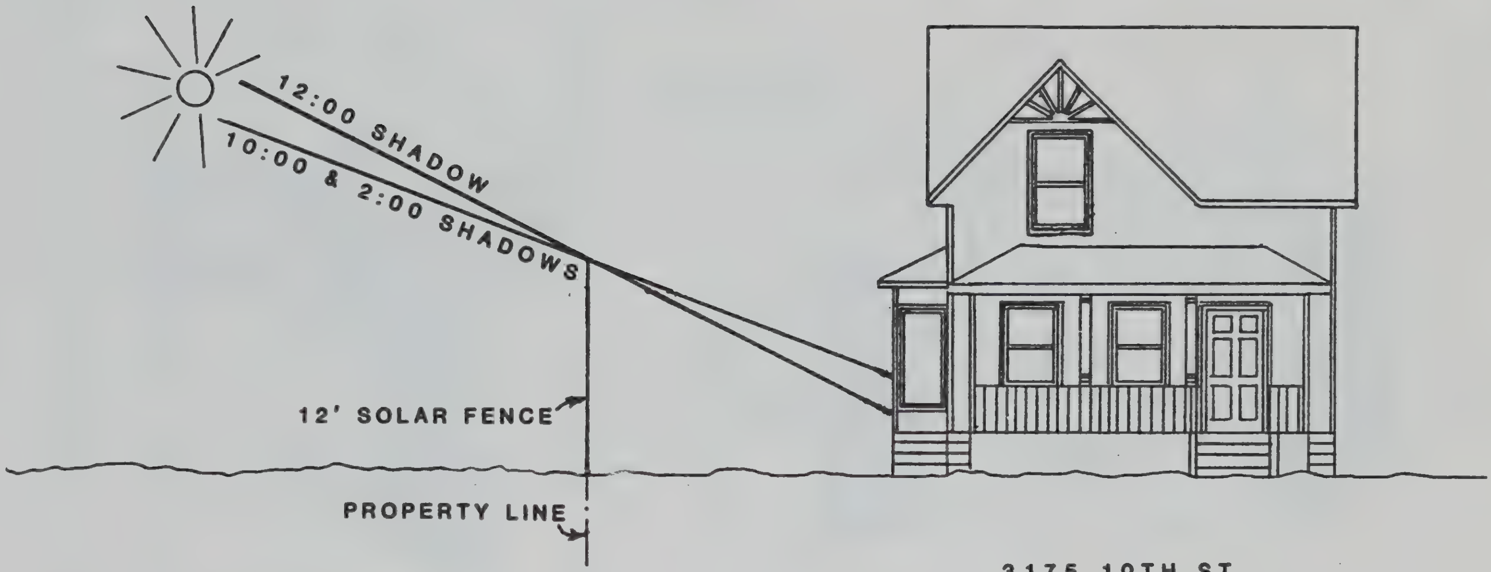


Figure 2. Street elevation showing winter solstice shadow of solar fence on 3175 10th Street

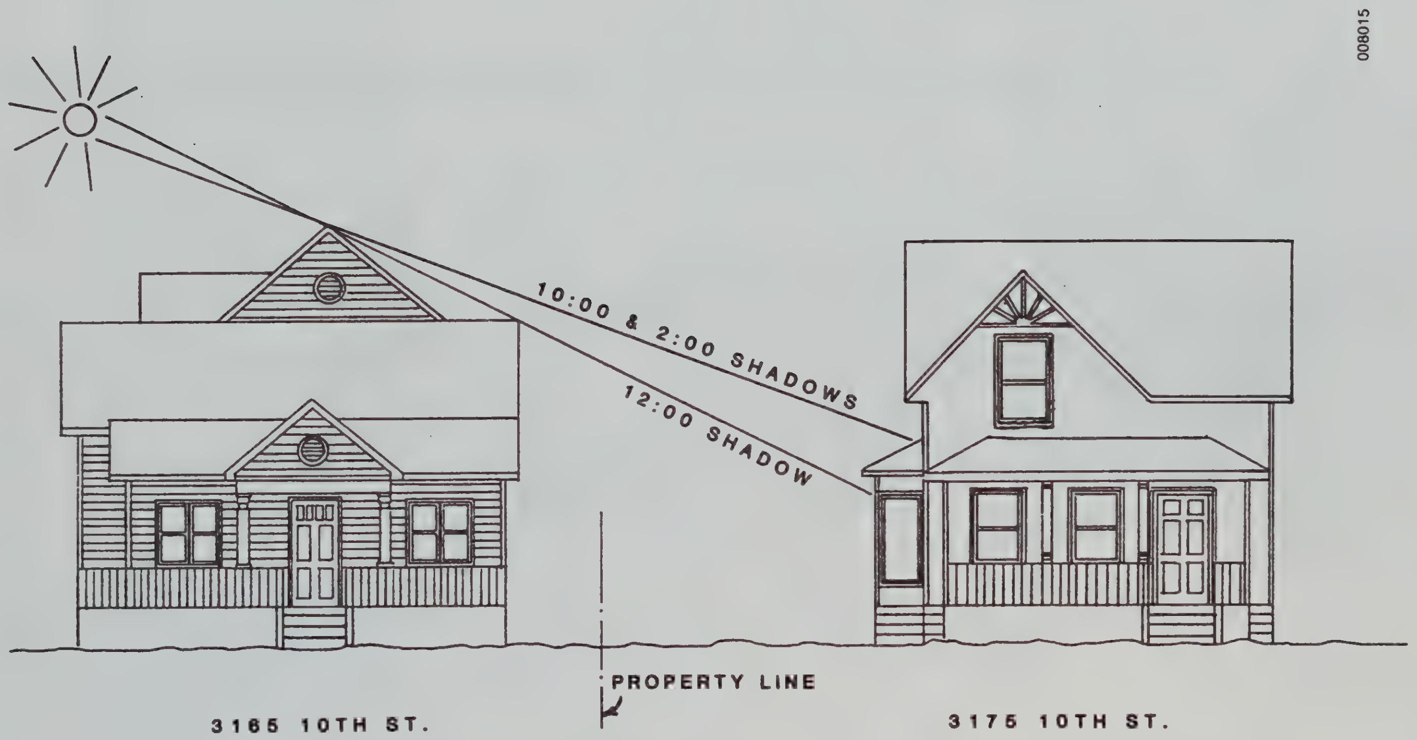


Figure 3. Street elevation showing winter solstice shadow of proposed structure at 3165 10th Street on 3175 10th Street

008016

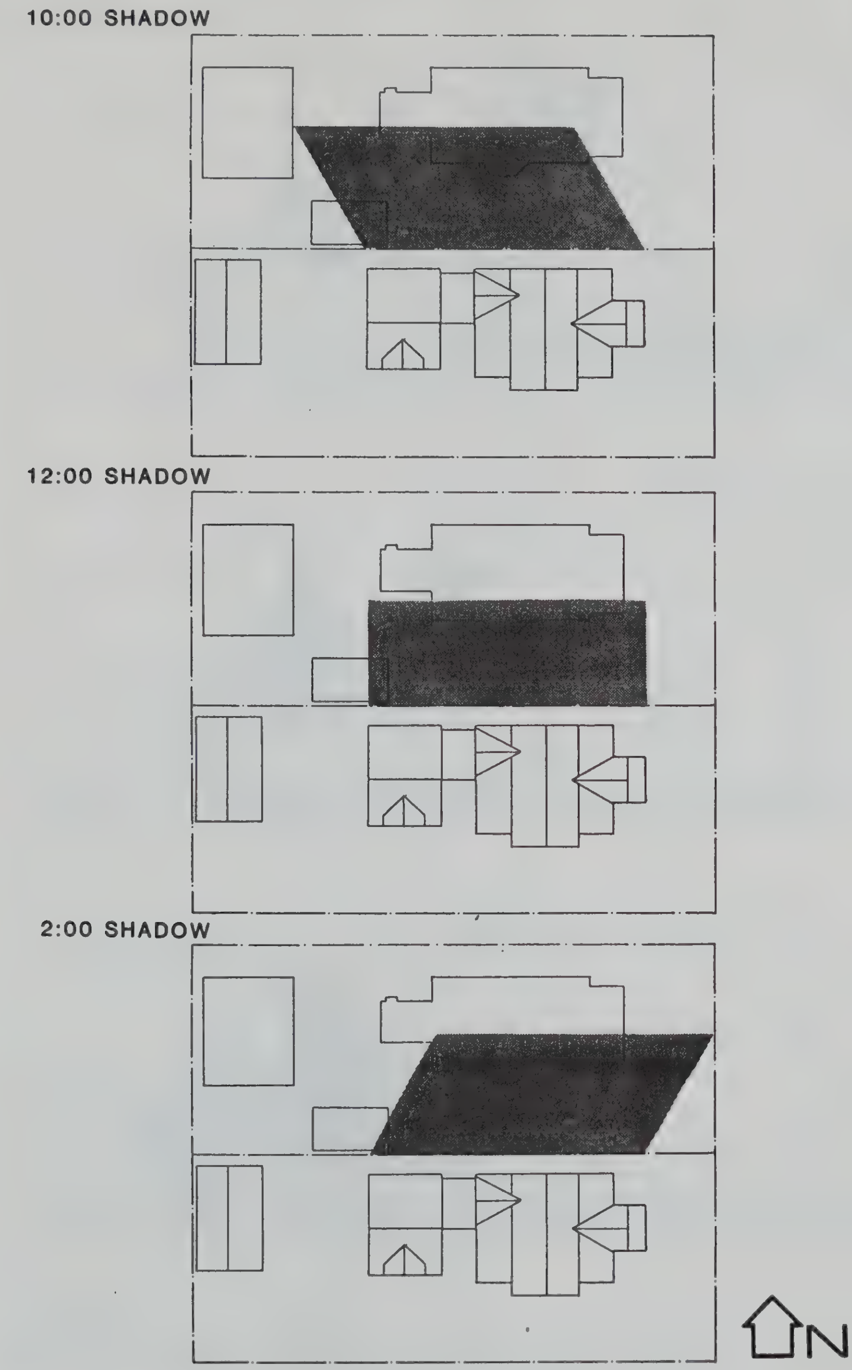


Figure 4. Plan view showing winter solstice shadow of solar fence on 3175 10th Street

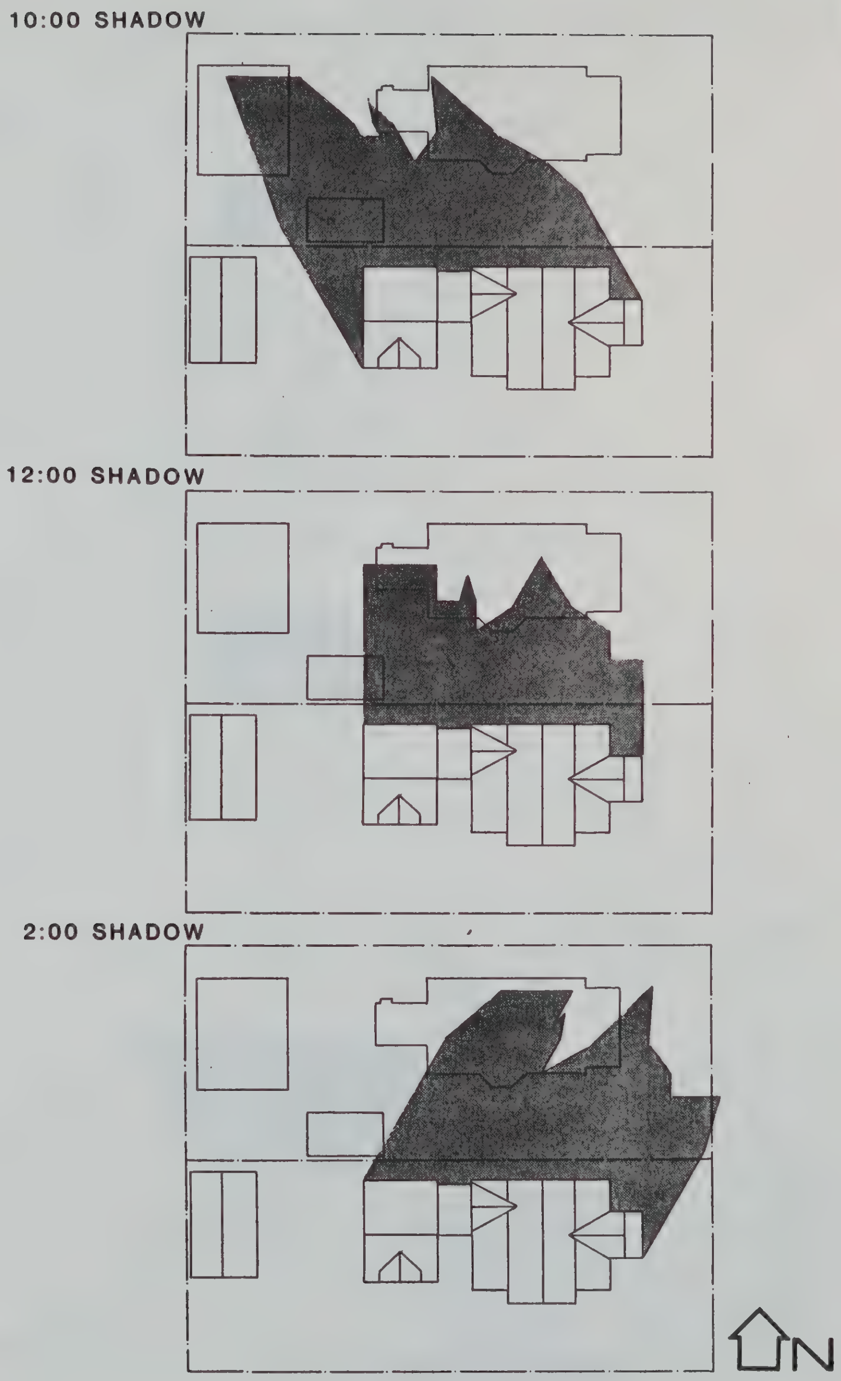


Figure 5. Plan view showing winter solstice shadow of proposed structure at 3165 10th Street on 3175 10th Street

008018

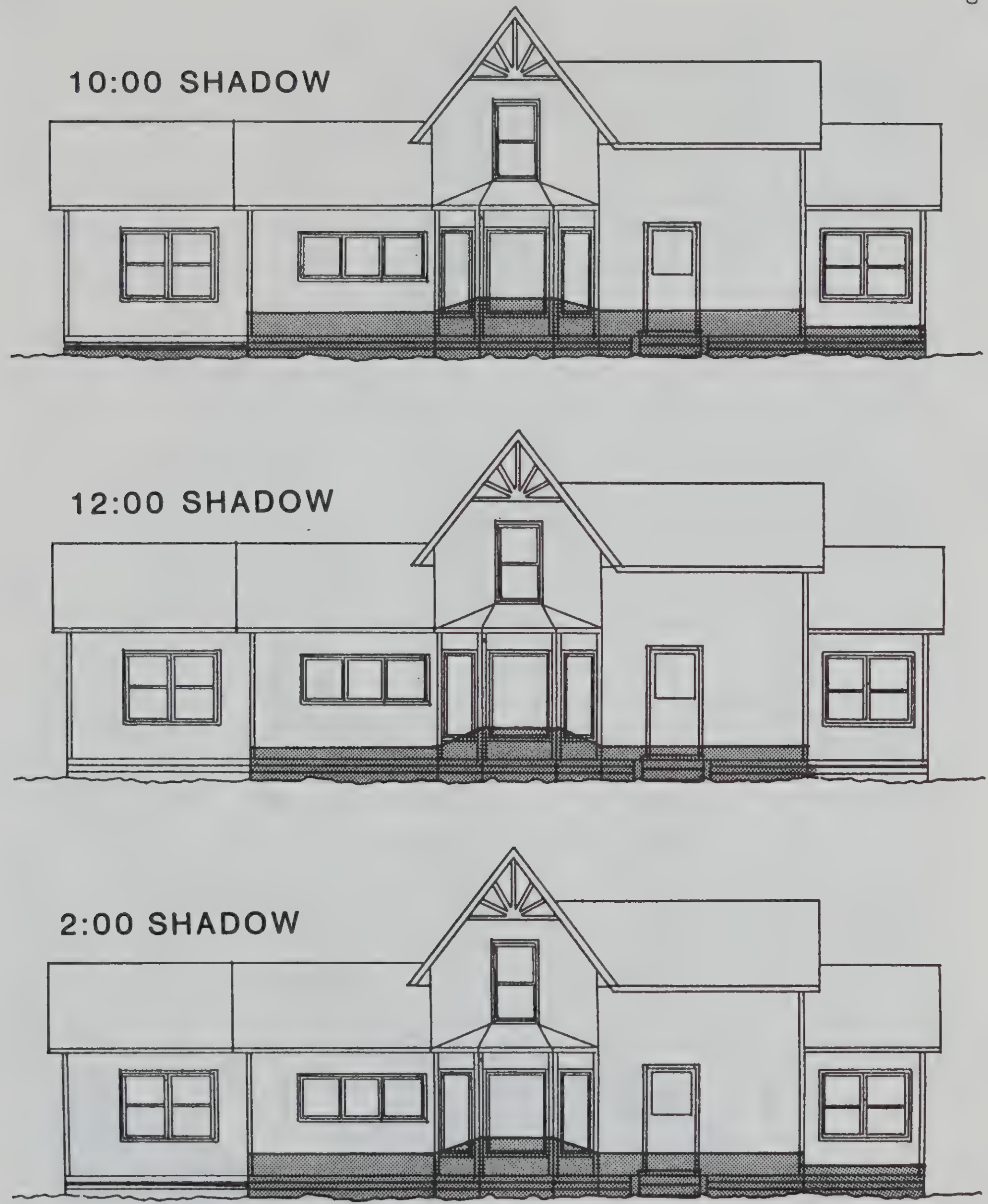
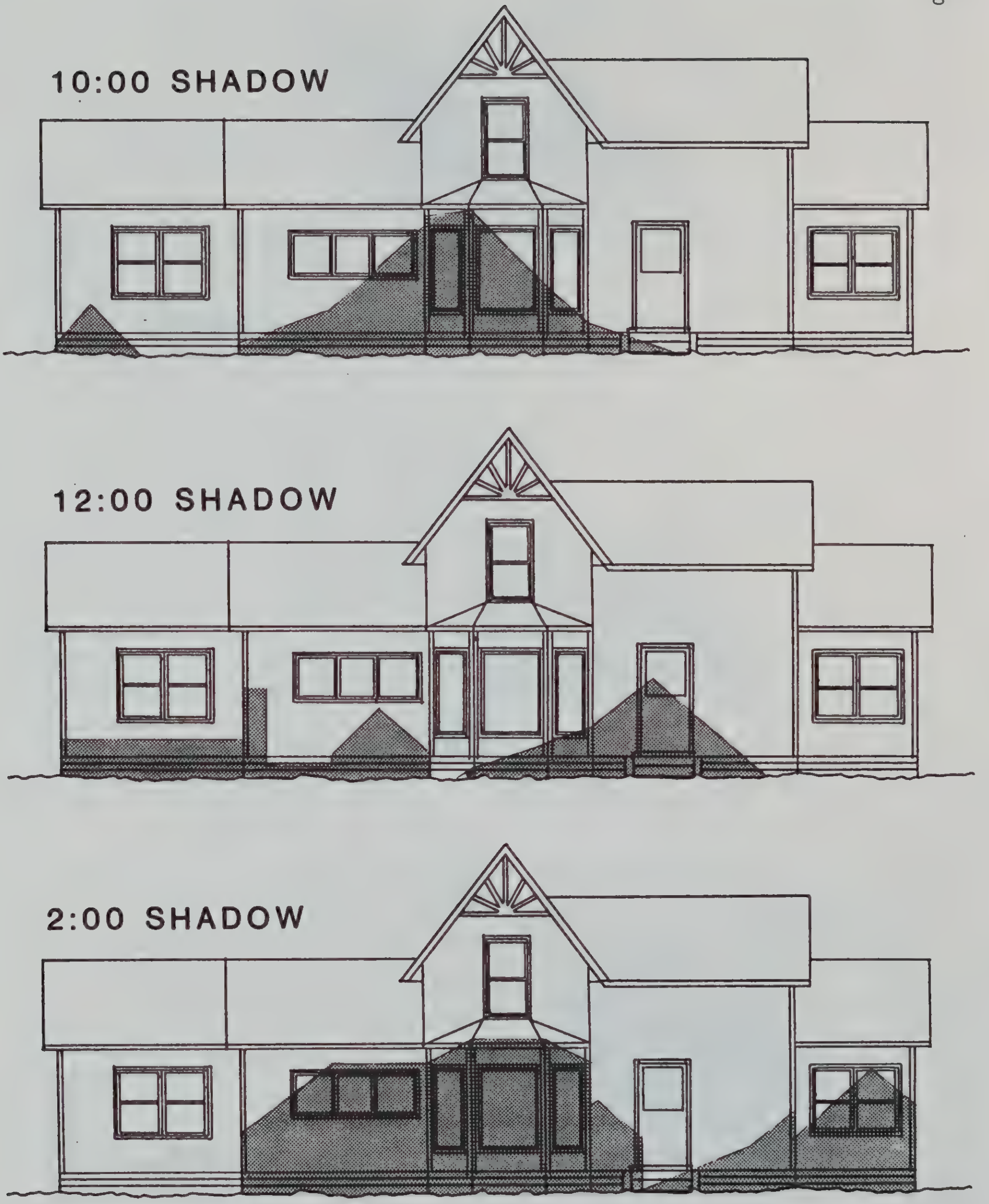


Figure 6. South elevation of 3175 10th Street showing the effect of the winter solstice shadow from the solar fence



10:00 SHADOW

12:00 SHADOW

2:00 SHADOW

Figure 7. South elevation of 3175 10th Street showing the effect of the winter solstice shadow from the proposed structure at 3165 10th Street

The Energy Advisory Board, Planning Board, and City staff have been struggling with developing a performance-based description of solar access desired in new developments so that no particular building orientation is prescribed but that a certain amount of sun is delivered to a certain amount of the south wall of a building. Even this performance-based measure has met with resistance from the development community. Their alternative would involve the use of an incentive for providing this shade-free area.

A third lesson is that people have not applied for solar access permits in the numbers that were originally expected even though Boulder has hundreds of solar installations. Thus far, three permits have been granted, all in one development. Several reasons for the low number of requests have been suggested: 1) the transaction cost of securing permit over a neighbor's objection is too high, 2) there are not many cases where a permit is needed, or 3) people simply do not know about it. The City has not performed an evaluation of the solar access program nor is one proposed.

Finally, we have learned that solar orientation requirements for residential and commercial buildings should not be the same. Boulder is just beginning to look at its commercial building code to identify energy conservation options. It is apparent that requiring an east-west orientation for commercial buildings for heating purposes is sometimes counter productive for buildings where internal heat loads from people, equipment, and lights often dominate. Although changes to the commercial energy code are not yet in place, Boulder's solar access code now requires that commercial buildings with large hot water demands provide adequate solar collector area. Specific strategies for daylighting and cooling will be encouraged in Boulder's commercial building code.

CONCLUSIONS

Despite a few difficulties associated with Boulder's solar access ordinance, it works; a solar fence approach to protecting solar access does protect solar potential. The Board or staff have not been willing to grant solar exceptions just because a solar system is not present or planned. Based on the lack of developer criticisms the solar siting requirement does not appear to have had an adverse effect on land use densities.

The major challenge for city planners and solar enthusiasts alike is to present the case for solar access protection in the absence of an energy crisis. If anything, the lesson for planning is that planning concepts tied to specific technologies only gain support as those technologies gain support. Speaking on the role of the energy crisis in the development of solar access techniques, Ralph Knowles (1981) said, "If that problem were suddenly solved by some economic, technological, or political breakthrough, or even if our rate of energy conversion could be miraculously doubled or tripled, we would still need to confront the basic issue of life quality." The principles of solar access cut directly to the issues of quality of life. Sunlight for courtyards, parks, people's yards, snow removal, daylighting and gardens are an important part of the quality of life. Unfortunately, this notion may get lost in all the discussion about flat-plate collectors and solar greenhouses.

REFERENCES

Danielson, Luke, 1982. Drafting a solar access ordinance: One city's experience. *Solar Access Law* 3(6):911-967.

Knowles, Ralph, 1981. *Sun, Rhythm, Form.* Cambridge, MA: MIT Press.

New York Times. July 15, 1979.

Passive Solar Journal, 4(2), 187-210 (1987)

Solar Irradiance on Vertical Surfaces

Thomas L. Stoffel
Eugene L. Maxwell
Richard E. Bird
Daryl R. Myers
Solar Energy Research Institute
1617 Cole Blvd.
Golden, Colorado 80401

Abstract

The solar radiation resource data available for passive design studies are generally measurements or model estimates of the global horizontal or direct beam solar irradiance or both. Several methods have been developed for converting these historical data to the solar irradiance available on a sloping surface.

We evaluated five such methods using a limited set of solar irradiance measurements taken at our outdoor laboratory over a 41-day period, 22 July to 4 September 1984. Our prelimary and limited results indicate all five algorithms overestimate (18%-46%) the solar irradiance on north-facing vertical surfaces and perform the best (±5%) for south-facing surfaces. Our estimate of the total measurement uncertainty associated with this analysis is ±5.6%.

INTRODUCTION

Passive solar heating, cooling, and daylighting design concepts require knowledge of the solar radiation incident on the walls, apertures, and other external building surfaces. In design performance simulations, these surfaces can generally be depicted as flat-plate collectors having a wide range of orientations described by various combinations of azimuth and elevation angles.

However, available measurements of solar radiation are limited to the global (direct beam + diffuse sky) radiation on a horizontal surface or the direct beam irradiance or both. This limitation is the result of two factors. The first factor is the need for a standard exposure of monitoring network instruments. By mounting the pyranometer in a horizontal position, the field of view of the measuring instrument is limited to the sky hemisphere, which, it is hoped, is not influenced by the local surroundings. Notably absent from these measurements are the potentially varying contributions from the ground reflection of solar radiation. We could then attribute any differences in the measurements between the stations in the monitoring network to the local atmospheric conditions. Second, it would be economically and technically impossible to equip a network of monitoring stations with enough pyranometers to measure all the possible combinations of surface orientations.

This disparity between available data and the need for design data on surfaces with varying orientations has resulted in the development of several algorithms for converting the direct beam and diffuse horizontal solar irradiance to estimates of the irradiance available to plane surfaces of any orientation (Hay and McKay, 1985).

APPROACH

In this study, we evaluated five conversion algorithms to estimate the irradiance on north-, east-, south-, and west-facing vertical surfaces. We designed and built a radiometer tower for measuring the necessary solar radiation components and compared the measured data with the estimated values from the algorithms.

DESCRIPTION OF THE ALGORITHMS

In general, the conversion algorithms attempt to account for the complex way the atmosphere influences solar radiation before encountering a building surface. The global radiation on a tilted surface is the sum of the direct (beam), diffuse (sky), and ground-reflected radiation components. The algorithms take the form

$$I_T(\beta,\phi) = I_S(\beta,\phi) + I_D(\beta,\phi) + I_G(\beta,\phi)\,, \tag{1}$$

where

$I_T(\beta,\phi)$ = global (total) irradiance on a tilted surface
$I_S(\beta,\phi)$ = direct irradiance on the tilted surface
$I_D(\beta,\phi)$ = diffuse sky irradiance on the tilted surface
$I_G(\beta,\phi)$ = ground-reflected irradiance on the tilted surface
β = the surface tilt angle, measured from the horizontal
ϕ = the surface azimuth angle relative to the sun.

The algorithms differ in the way each of these components is estimated before being summed.

Contribution of the Direct Irradiance

Each of the five algorithms uses the same relationship based on solar position relative to the surface to predict the direct solar irradiance (beam) component available on a tilted surface:

$$I_S(\beta,\phi) = I\cos\theta\,, \tag{2}$$

where

I = the intensity of the direct normal irradiance
θ = the angle of incidence between the direct rays and the normal to the surface.

Viewed from earth, the sun would subtend a 0.5° field of view based on purely geometric considerations. However, radiation from the solar disk that is transmitted through a cloudless atmosphere is scattered forward, creating a circumsolar region. The amount of circumsolar radiation depends on the amount of water vapor, aerosols, and other atmospheric constituents.

A pyrheliometer mounted in a sun-following tracker measures the direct normal solar irradiance. To accommodate the possible variations in tracker alignment during unattended operation, the pyrheliometer commonly used for resource monitoring has at least a 5.0°-5.7° field of view (Coulson, 1975). Therefore, data from this instrument contain most of the circumsolar radiation component.

Contribution of the Diffuse Sky Irradiance

Determining the distribution of diffuse solar irradiance from the sky hemisphere that is available to a surface with arbitrary orientation is the most challenging aspect of developing a method for estimating the total radiation on a tilted surface. The earliest approach assumed an isotropic, or uniform, distribution of the diffuse sky irradiance. Atmospheric variability seldom allows this uniform distribution. Under clear sky conditions, the interaction of the solar radiation with the cloudless atmosphere produces horizon brightening. Conversely, overcast skies produce horizon darkening. The nonuniform distribution of diffuse irradiance in the sky dome is called anisotropy.

Isotropic Algorithm

The diffuse sky term of this algorithm is based on the assumption of uniformly distributed diffuse sky radiation (Kondratyev, 1969; Liu and Jordan, 1960):

$$I_D(\beta) = 1/2\, I_D(0)\,(1 + \cos\beta)\,, \tag{3}$$

where

$I_D(0)$ = the measured diffuse sky irradiance on a horizontal surface ($\beta = 0$)

β = the surface tilt angle with respect to the horizontal.

This expression assumes uniform radiance from each portion of the sky; i.e., isotropic diffuse irradiance from all directions above the surface, resulting in no dependence on azimuth angle ϕ.

Temps and Coulson Algorithm

Temps and Coulson (1977) added a degree of complexity to the isotropic diffuse sky term by introducing an anisotropic modifier to account for horizon brightening and circumsolar radiation:

$$I_D(\beta) = 1/2\, I_D(0)\,(1 + \cos\beta)\, M_1\, M_2\,, \tag{4}$$

where

$M_1 = [1 + \sin^3(\beta/2)]$

and

$M_2 = (1 + \cos^2\theta \sin^3 Z)$

where

θ = the incidence angle of the direct normal irradiance on the surface

Z = the solar zenith angle.

This algorithm is only appropriate for clear sky conditions because the anisotropic modifier M_2 does not account for the increase in circumsolar radiation with the onset of cloud cover. Notice that for the case of $\beta = 0$, horizontal orientations, the incidence angle θ equals the solar zenith angle Z, and this modifier continues to account for the circumsolar contributions to anisotropy of the diffuse radiation field. Also, the modifier M_1 is to account for horizon brightening, which under overcast skies should account for horizon darkening.

Klucher Algorithm

A refinement of the diffuse sky term provided by Klucher (1978) adds a cloudiness function F to the Temps and Coulson algorithm:

$$I_D(\beta) = 1/2\, I_D(0)\,(1 + \cos\beta)\, M_3\, M_4\,, \tag{5}$$

where

$$M_3 = [1 + F \sin^3 (\beta/2)]$$

$$M_4 = [1 - F \cos^2 \theta \sin^3 Z]$$

$$F = \{1 - [I_D (0)/I_T (0)]^2 \} .$$

With overcast skies, the global irradiance equals the diffuse irradiance, and the diffuse sky term reduces to the isotropic form.

Hay Algorithm

The diffuse sky term developed by Hay and Davies (1980) introduces the concept of an anisotropic index that is the ratio of the direct normal irradiance at the earth's surface to the extraterrestrial direct normal irradiance:

$$\begin{aligned} I_D (\beta) = I_D (0)[&(I \cos \theta/I_o \cos Z) \\ &+ 1/2(1 + \cos \beta)(1 - I/I_o)] , \end{aligned} \tag{6}$$

where

I = direct normal (beam) irradiance

I_o = extraterrestrial direct normal irradiance.

The first term inside the brackets represents circumsolar radiation. The intensity of this irradiance is made a function of the atmospheric transmissivity I/I_o, the angle of incidence of the direct irradiance, and the solar zenith angle. The inverse relation with cos Z represents an increase in circumsolar radiation with an increase in air mass (increasing solar zenith angle). The second term accounts for the increasing diffuse radiation that accompanies increasing cloud cover or atmospheric turbidity. The Hay algorithm simplifies to the isotropic case for overcast sky conditions.

Perez Algorithm

Perez (Perez and Stewart, 1984) has developed an algorithm that also accounts for horizon brightening and circumsolar radiation. These conditions are addressed by describing the sky dome as isotropic except for a circular region of variable size around the sun and a horizontal band of variable height at the horizon. The equation for the diffuse sky term of the Perez algorithm is:

$$I_D(\beta) = I_D(0)\,\frac{1/2(1 + \cos\beta) + 2(F_1 - 1)(1 - \cos\alpha)Z_c}{1 + 2(F_1 - 1)(1 - \cos\alpha)\,Z_h} \qquad (7)$$

$$\frac{+\,2(F_2 - 1)\,\xi/\pi\,\sin\xi'}{+\,1/2(1 - \cos 2\xi)(F_2 - 1)},$$

where

F_1 = ratio of the radiance in the circumsolar region to isotropic sky radiance

F_2 = ratio of the radiance in the horizon band to the isotropic sky radiance

α = half-angle width of the circumsolar region

ξ = angular width of the horizon band

ξ' = altitude angle of the apex of the horizon band with respect to the tilted surface

$Z_c = \cos\theta \qquad [0 < \theta < (\pi/2 - \alpha)]$

$Z_c = \dfrac{(x_c \sin x_c)}{\alpha} \qquad [(\pi/2 - \alpha) < \theta < (\pi/2 + \alpha)]$

$Z_c = 0 \qquad [\theta > (\pi/2 + \alpha)]$

$x_c = (\pi/2 + \alpha - 0)/2$

θ = angle of incidence of circumsolar radiation on a tilted surface

$Z_h = \cos Z \qquad [0 < Z < (\pi/2 - \alpha)]$

$Z_h = \dfrac{(x_h \sin x_h)}{\alpha} \qquad [Z > (\pi/2 - \alpha)]$

$x_h = (\pi/2 + \alpha - Z)/2$

Z = angle of incidence of circumsolar radiation on a horizontal surface.

The terms F_1 and F_2 are empirically derived from measured data at the location of interest. They are a function of the solar zenith angles, I_D (0) and I(0). They are available in the form of 5 × 6 × 7 matrixes for the solar monitoring station at the State University of New York at Albany.

The Ground-Reflected Term

One can estimate the solar irradiance reflected by the ground onto a tilted surface by assuming either isotropic (uniform with respect to direction) or anisotropic (directional) reflections. With the exception of the Temps and Coulson and Klucher algorithms, the five methods we evaluated in this study assumed isotropy for this contribution of solar irradiance.

Temps and Coulson Algorithm

The Temps and Coulson algorithm was developed from measurements taken at the University of California at Davis. The technique accounts for the azimuthal dependence of the ground-reflected diffuse radiation component:

$$I_G(\beta,\phi) = I_T(0)\, R_G\, M_5\, M_6 \,, \tag{8}$$

where

$M_5 = [1 - \cos^2(\beta/2)]$

$M_6 = [1 + \sin^2(Z/2)\,|\cos\phi|]$

ϕ = azimuth angle of the tilted surface relative to the sun ($\phi = 0$ when the surface is pointed toward the sun).

The equation represents a ground surface exhibiting forward scattering that increases with solar zenith angle.

The Klucher algorithm was developed from data collected at NASA Lewis, Cleveland, Ohio, using pyranometers shielded from the ground-reflected radiation by artificial ground planes.

Isotropic Ground Reflection

The solar radiation reflected by the ground onto a tilted surface can be estimated by

$$I_G(\beta) = 1/2\, I_T(0) R_G\, (1 - \cos\beta) \,, \tag{9}$$

where

$I_T(0)$ = global horizontal irradiance

R_G = ground albedo.

This technique assumes the reflecting surface is a homogeneous and perfect diffuser (Labertian) surrounding the tilted surface of interest.

Table 1 summarizes the five algorithms we evaluated; it also classifies the general character of the diffuse sky and ground-reflected irradiance terms.

Table 1. Classification of Five Solar Irradiance Conversion Algorithms

Algorithm	Diffuse Sky Term	Ground Term
Isotropic	Clear or cloudy and isotropic	Isotropic
Temps and Coulson	Clear only and anisotropic	Anisotropic
Klucher	Clear or cloudy and anisotropic	None
Hay	Clear or cloudy and anisotropic	Isotropic
Perez	Clear or cloudy and anisotropic	Isotropic

MEASUREMENTS AT THE SOLAR RADIATION RESEARCH LABORATORY

Pyranometers were installed at the Solar Radiation Research Laboratory (SRRL) of the Solar Energy Research Institute, Golden, Colo., using the radiometer tower designed for monitoring solar irradiance on vertical surfaces oriented in the four cardinal directions (Figure 1). We positioned the instruments to measure the global irradiance on each of the four vertical surfaces, as well as the diffuse sky and ground-reflected components for the north- and south-facing orientations by incorporating an artificial horizon into the tower's support structure. We measured the solar radiation reflected onto a downward-facing horizontal surface by mounting an inverted pyranometer on the tower 5 ft (1.7 m) above the ground.

We completed the necessary data collection by including the global horizontal and direct normal solar measurements available from the

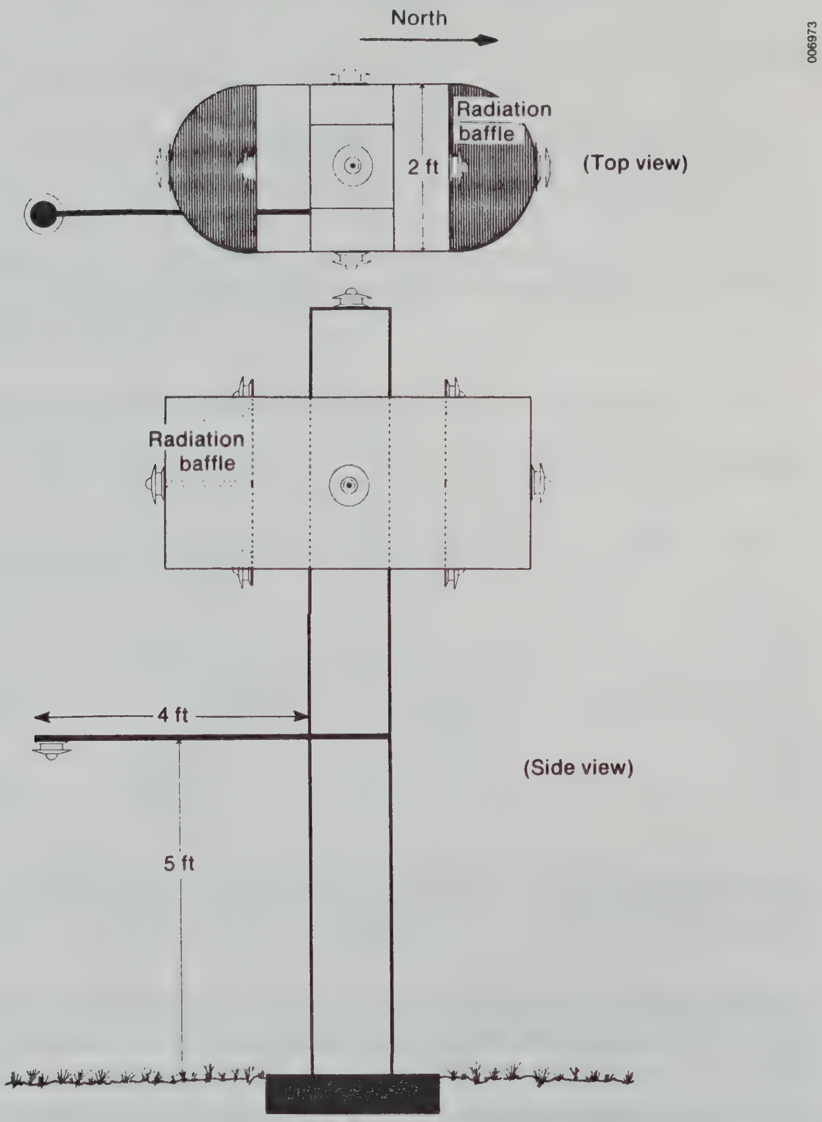


Figure 1. Radiometer tower for measuring solar irradiance on vertical surfaces [overall height of tower = 10 ft (3 m)]

baseline monitoring equipment already in place at SRRL. The measurements we used in our evaluations were 15-min averages of 10-sec instantaneous scans of the data channels.

Pyranometer Comparisons

All the Eppley Laboratory model PSP pyranometers used for our study were calibrated and intercompared by placing them on a large tilt table with the Solar Energy Research Institute's working standard PSP and by collecting periods of global data for horizontal, south-facing vertical, and north-facing vertical orientations. We obtained and analyzed several days of 1-min data for each orientation (Figure 2). Figure 3 illustrates the relative performance of the test pyranometers with respect to the reference unit. These intercomparisons cannot ensure the absolute measurement accuracy of the pyranometers. The reference pyranometer can itself undergo changes in sensitivity when instrument orientation, ambient air

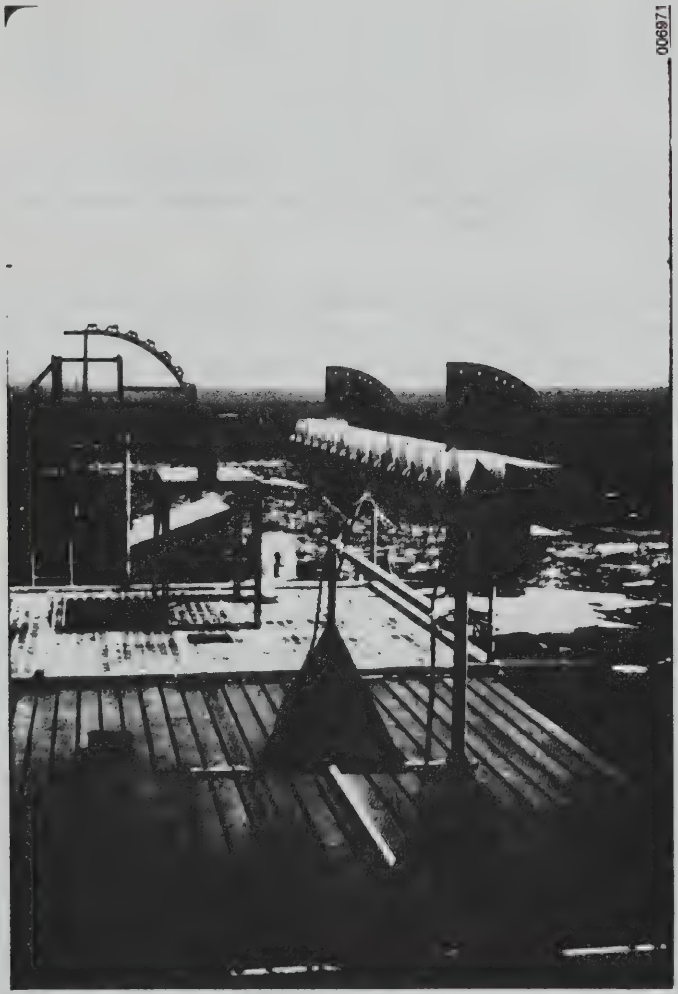


Figure 2. Pyranometer comparisons using tilt table in north-facing vertical position

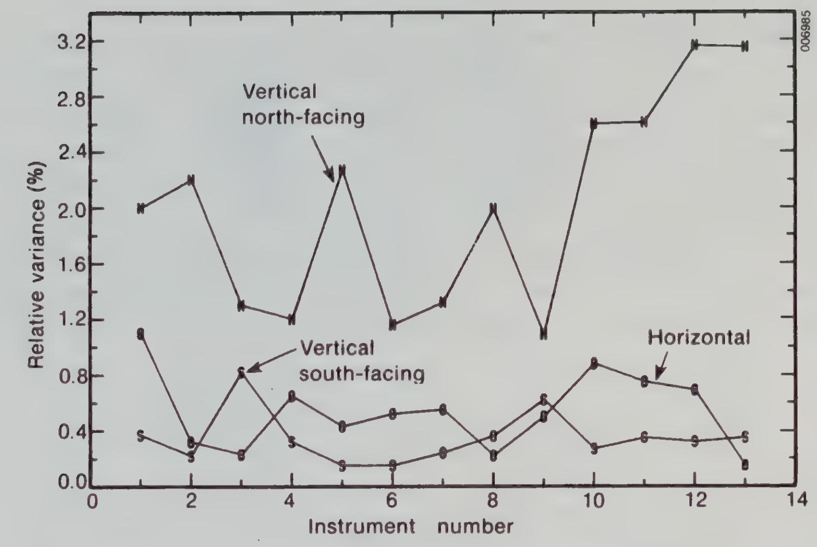


Figure 3. Results of pyranometer comparisons using tilt table mounting platform in horizontal (0), south-facing (S), and north-facing (N) vertical positions

temperature, solar irradiance levels, or other measurement conditions change. The overall agreement of the calibrations is within the generally accepted tolerance of ±5% for these thermopile instruments (SERI, 1982).

Selected Daily Profiles

Figure 4 shows the symmetry of the global irradiance available on vertical surfaces during a very clear day (10 August 1984). It is particularly interesting to note the irradiance on all four surfaces is about the same in the absence of the direct radiation when the sun passes behind the surface. Furthermore, the daily total energy received on east- (1575 Btu/ft^2, 17.9 MJ/m^2), south- (1188 Btu/ft^2, 13.5 MJ/m^2), and west-facing (1540 Btu/ft^2, 17.5 MJ/m^2) vertical surfaces is about the same for this midsummer day in Golden, Colo.

Data for a partly cloudy day (6 September 1984) are shown in Figure 5. On this day, very thin cirrus clouds developed late in the afternoon. From these data, an interesting relationship is evident between the north-vertical diffuse sky irradiance and the north-vertical ground-reflected irradiance components. In early morning and late afternoon, the diffuse sky irradiance reaches a maximum, and its values are greater than the ground-reflected values. By

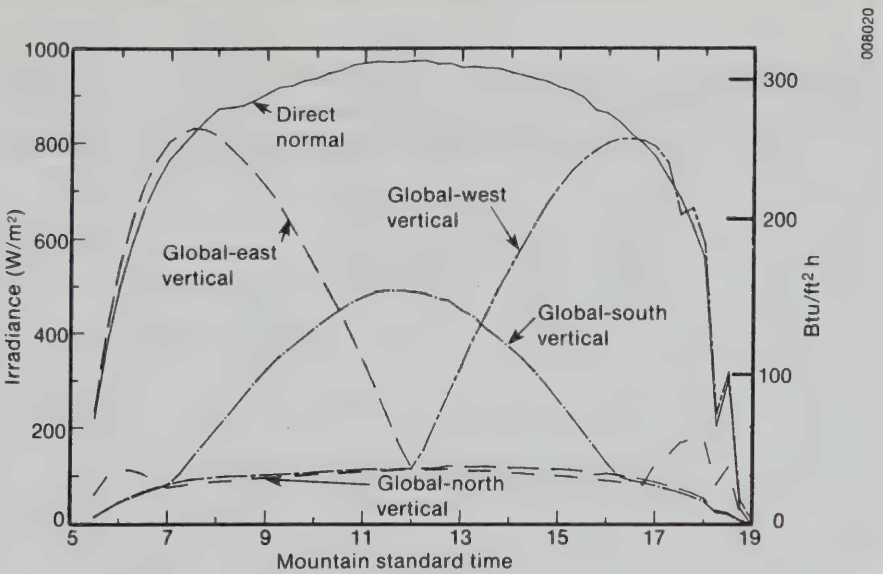


Figure 4. A selected clear day (10 August 1984) of 15-min averaged measurements

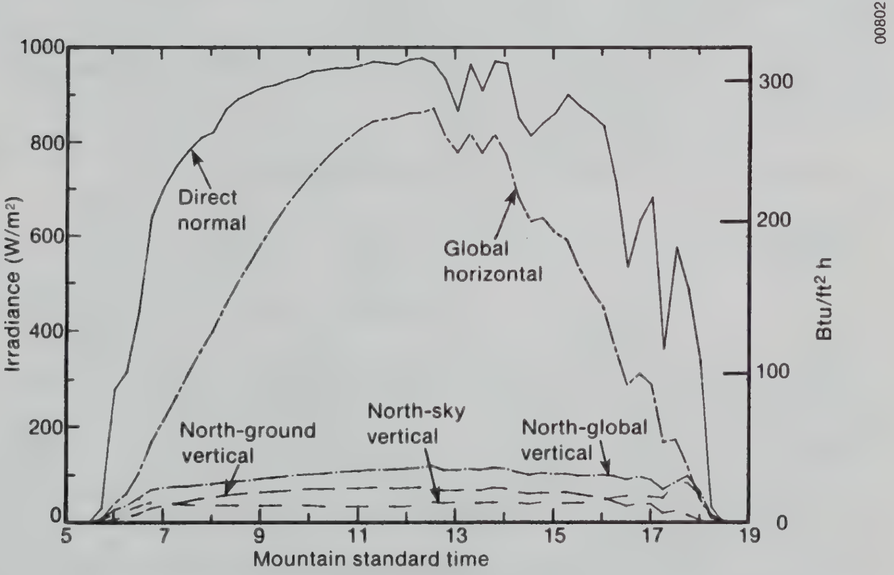


Figure 5. Measurements for a partly cloudy day (thin cirrus) (6 September 1984)

midmorning, the ground-reflected irradiance levels are about twice the diffuse sky levels. This relationship is consistent with the gradual increase in the global horizontal irradiance.

The ground around the radiometer tower was a natural surface with grass and some bare soil. At this time of year, the vegetation is mostly dry. The measured albedo ranged from 15% to 18% for the day.

Figure 6 presents irradiance measurements on vertical surfaces for another partly cloudy day (7 September 1984). Early in the morning, a cold front moved through the area, producing a dark layer of altostratus clouds that moved from the northwest early in the morning; most of the sky was covered with opaque clouds by 0830 mountain standard time (MST). These stratus clouds produced a sky irradiance component on the north-facing vertical surface that was nearly double the ground-reflected component. The opposite relationship was true for the relative levels observed on the previous clear day. At about 1230 MST, the stratus clouds began to break up, and at about 1315 MST, the ground irradiance exceeded the contribution from the diffuse sky on the north-facing surface. The presence of altocumulus clouds with portions of clear sky in the afternoon produced the varying levels of direct radiation and maintained the diffuse sky irradiance at about the same level as the ground-reflected contribution.

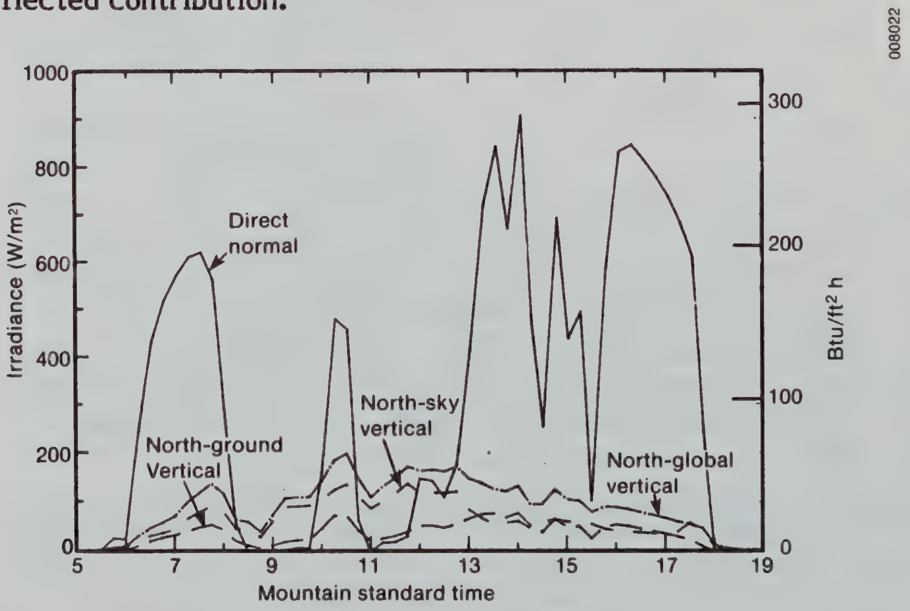


Figure 6. **Effects of partly cloudy (opaque) conditions on north-facing surface (7 September 1984)**

The irradiance received on a cloudy day, 6 August 1984, is shown in Figure 7. Some direct (beam) irradiance was recorded between 0500 and 0800 MST. Between 0800 and 1030 MST, a low overcast of cirrostratus clouds developed, obscuring the direct radiation. This cloud cover thinned between 1030 and 1330 MST but was nearly uniform across the sky dome. Precipitation did not interfere with the pyranometer measurements on this day.

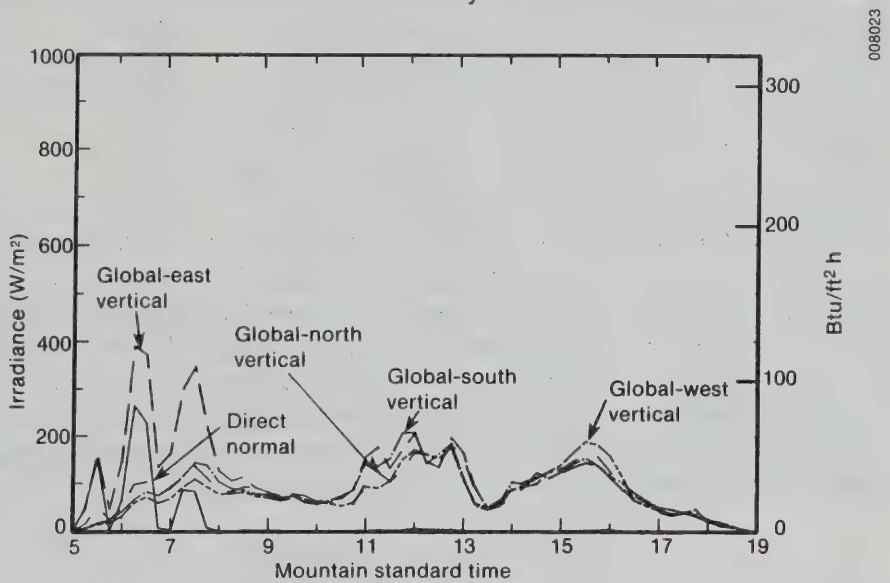


Figure 7. **Measurements for a selected overcast day (cirrostratus) in August**

EVALUATION OF THE ALGORITHMS

We compared measured global irradiance data on north-, east-, south-, and west-facing vertical surfaces from 22 July to 4 September 1984, with the corresponding estimates from the five algorithms using the measurements of direct normal and global horizontal irradiance. Table 2 documents the average percent root mean square (%rms) and the average percent mean bias error (%mbe) for the 41 days of measurements. The %rms is a measure of the variation of predicted values around the measured values. The %rms is always positive. A few large variations in the comparisons can substantially increase the %rms. The %mbe is an indication of the average deviation of the predicted values from the measured data. A positive %mbe indicates that the algorithm overpredicts the irradiance.

Table 2. Conversion Algorithm Performance Summary

	Vertical Surfaces			
Azimuth	North	East	West	South
%rms				
Isotropic	61.6	29.1	33.0	17.9
Temps and Coulson	96.5	31.4	50.9	31.9
Klucher	68.9	29.6	34.5	20.5
Hay	60.4	28.3	32.4	18.0
Perez	55.5	26.6	32.2	19.6
%mbe				
Isotropic	18.5	-3.0	3.4	1.5
Temps and Coulson	46.5	9.5	23.1	15.3
Klucher	29.2	2.1	11.1	6.8
Hay	14.6	-3.0	2.9	0.9
Perez	18.0	1.9	10.6	6.7

For the evaluation of the algorithms, we computed the diffuse horizontal irradiance from the measurements of global horizontal and direct normal irradiance components using

$$I_D(0) = I_T(0) - I \cos Z , \tag{10}$$

where

$I_D(0)$ = diffuse horizontal irradiance

$I_T(0)$ = global horizontal irradiance, measured with pyranometer

I = direct normal irradiance, measured with pyrheliometer

Z = solar zenith angle for the midpoint of the 15-min data period.

We also added the isotropic ground term computation to the Klucher and Perez algorithms to complete the comparisons using the measured ground albedo values.

Table 2 shows that the %rms is lowest for the south-facing surface, much higher on east- and west-facing surfaces, and very high on the north-facing surface. These conditions can be attributed in part to the generally lower levels of irradiance available on north-facing slopes, as shown in Table 3. The %mbe statistics in Table 2 show reasonable performance on east-, south-, and west-facing surfaces with the exception of the Temps and Coulson algorithm, which has no cloud-cover term.

Table 3. Average Daily Total Irradiance on Vertical Surfaces (Golden, Colo., 22 July-4 September 1984)

Orientation	Irradiance Btu/ft^2/day	 KJ/m^2/day	Percent of North
North	437	4967	100
East	1288	13,950	281
South	924	10,495	211
West	777	8832	178

We made a detailed evaluation of the algorithms with the anisotropic diffuse sky term using measured data for two specific days. The first day, 6 September 1984, was generally clear, although scattered clouds developed in the afternoon. This situation is apparent in Figure 8, which shows the direct normal, global horizontal, and calculated diffuse horizontal components as recorded on this day.

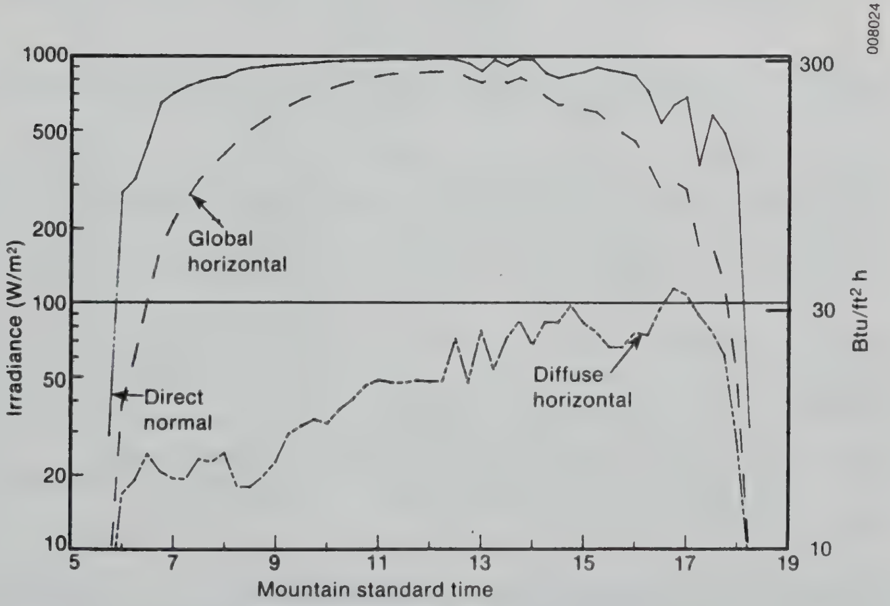


Figure 8. Solar component measurements (6 September 1984)

The comparison of the measured and estimated values of irradiance on a north-facing vertical surface for 6 September is shown in Figure 9. In general, the estimates are close to the measured data except during the morning period. In the afternoon, the scattered clouds produced very erratic results; however, in the late afternoon, the skies apparently cleared again. None of the algorithms deals well with scattered clouds.

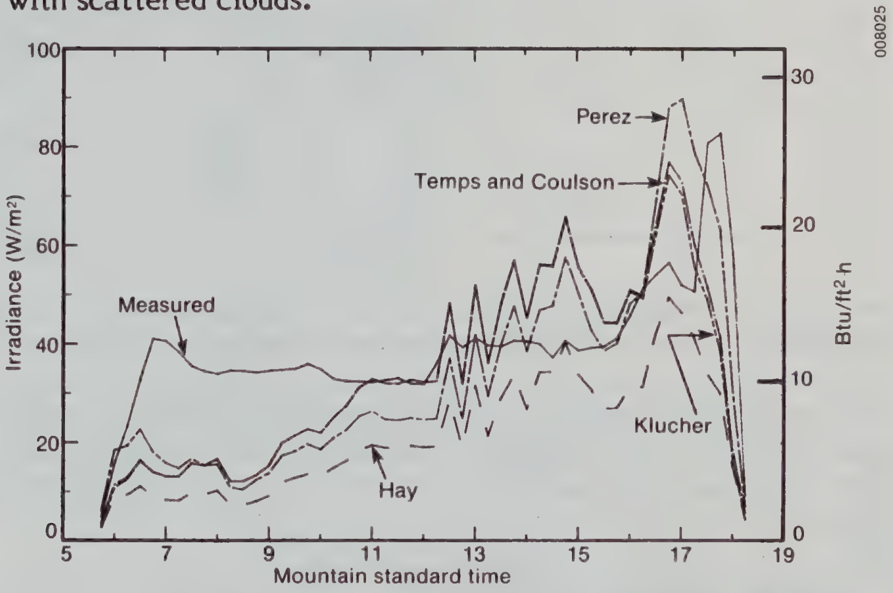


Figure 9. Comparison of measured data and model estimates for irradiance on north-facing vertical surfaces (6 September 1984)

Figures 10 and 11 are similar plots for a partly cloudy day, 7 September 1984. On this day, all the models overestimated the irradiance on a north-facing vertical surface except during the relatively clear periods in the early morning and late afternoon.

Figure 12 compares the measured and estimated ground-reflected irradiance on a north-facing vertical surface for 7 September. Relatively good agreement is indicated between the isotropic and anisotropic methods under clear and cloudy sky conditions.

UNCERTAINTY ANALYSIS

A review of the measurement uncertainty and the input sensitivity of the algorithms is needed before evaluating their performance with sample data. We apply the techniques of Abernethy and Ringhiser (1985) in this analysis.

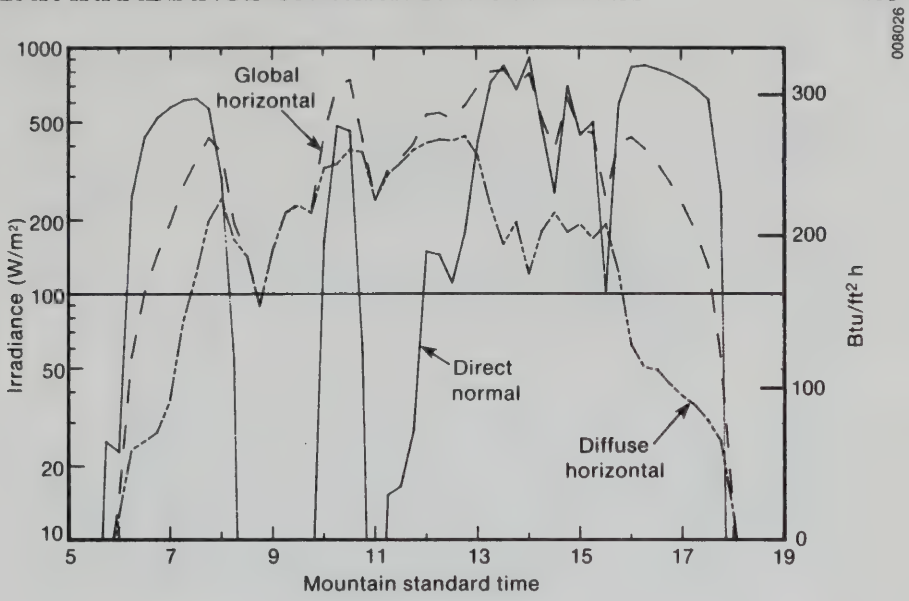


Figure 10. Solar component measurements (7 September 1984)

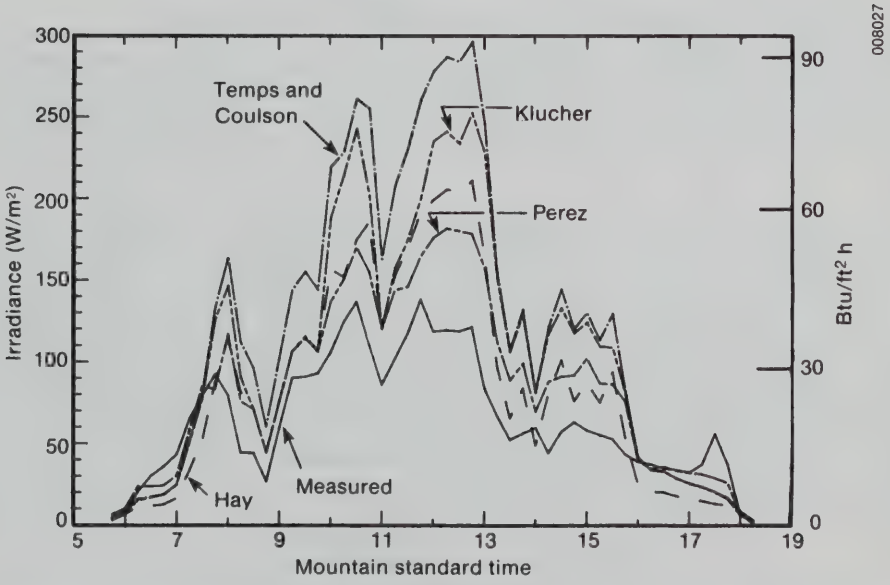


Figure 11. Comparison of measured data and model estimates for irradiance on north-facing vertical surfaces (7 September 1984)

The goal of uncertainty analysis is to adequately identify sources of error and combine them in order to estimate the largest error that can reasonably be expected for a particular measurement process. We must differentiate between two types of error that contribute to

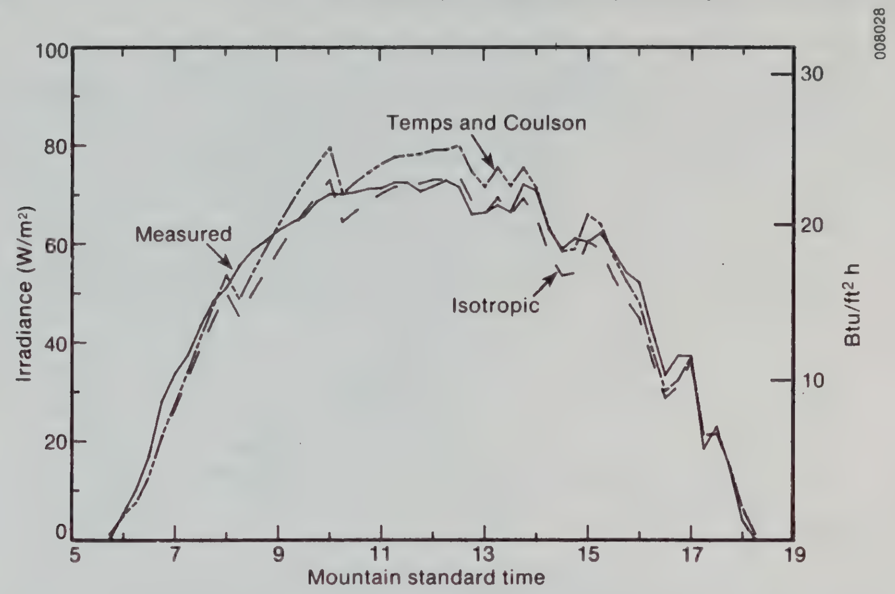


Figure 12. **Measured and modeled ground-reflected irradiance on a north-facing vertical surface (7 September 1984)**

measurement uncertainty. Random error, also referred to as repeatability, precision, or sampling error, can be quantified by the standard deviation of the usually normal or Gaussian probability distribution of the observations with respect to the mean or average value.

The second error type describes the offset between the mean of the normal distribution and the true value. Sometimes referred to as the calibration error, this component of measurement uncertainty can be estimated by considering all aspects of the calibration, acquisition, and reduction phases of the experimental process. The individual random (Ri) and bias (Bi) errors can be combined into final values for each error type by using the square root of the sum of the squares of each possible error source:

$$R = \sqrt{\Sigma\ Ri^2} \qquad B = \sqrt{\Sigma\ Bi^2}\ . \tag{11}$$

The total uncertainty can be determined by combining the two types of errors using the Root Sum Squaring Method. This method defines a confidence interval that gives a 95% probability of the true value within the interval ± Urss:

$$Urss = \sqrt{(t_{95}\ R)^2 + B^2} \tag{12}$$

where

t_{95} = student's T distribution factor based on the degrees of freedom.

For this study, the degree of freedom (sample size less the number of calculated parameters) is greater than 30, and therefore, t_{95} is 2.0.

To illustrate the application of this analytic technique, the total measurement uncertainty associated with the pyranometer data is presented in Table 4. The values assigned to the bias and random error components are based on instrument characterization data and estimates from past experience. Our intent is to account for all possible sources of error using the best available information.

Table 4. Pyranometer Measurement Uncertainty (Root Sum Squaring)

Error Source	Bias (%)	Random (%)	Total (%)
Reference Pyranometer Calibration	1.8	0.8	2.4
Pyranometer Characteristics			
Temperature response	0.4	0.3	0.7
Cosine response	1.0	0.5	1.4
Azimuth response	1.0	0.5	1.4
Linearity	0.1	0.1	0.2
Spectral response	0.1	0.1	0.2
Thermal electromotive force (EMF)	0.1	0.1	0.2
Orientation (leveling/tilt)	0.5	0.5	1.1
Dome cleanliness	2.0	1.0	2.8
Data-Acquisition System	0.1	0.1	0.2
Total Uncertainty	3.1	1.6	4.4

The input for the conversion algorithms shares a common data set, as shown in Table 5. The calculation of the solar zenith angle is an important intermediate calculation used by the algorithms. Our sensitivity study has shown that the uncertainties associated with the input data set produce uncertainties in the cosine of the zenith angle on the order of < 1.0% for air mass < 5.0 (solar zenith angle < 78.5°).

Table 5. Uncertainty of Common Input Parameters

Parameter	Uncertainty
Time of Day	±10 sec
Station Latitude	±0.01°
Station Longitude	±0.01°
Solar Declination	±0.04°
Equation of Time	±30 sec
Solar Constant	±7 W/m^2

The uncertainty associated with the value for the solar constant is another consideration when determining algorithm performance. The value used for the solar constant in this study was 1377 W/m^2. The uncertainty associated with this value is ±0.5% based on recent measurements made in space (Hickey et al., 1986).

Using Equation 12 to combine all the sources of error, we arrived at the final estimate of total uncertainty for this study, 5.6% (Table 6). The evaluation of algorithm performance must account for this degree of uncertainty in the experimental process. Significant differences between the model estimates and the measured data must exceed the total uncertainty (±5.6%).

Table 6. Total Uncertainty (Root Sum Squaring)

Error Source	Bias (%)	Random (%)	Total (%)
Pyranometer	3.1	1.6	4.4
Pyrheliometer	1.8	1.3	3.2
Algorithm Input Data			
Solar geometry	1.0	0.2	1.1
Solar constant	0.5	0.2	0.6
Algorithm Output Data (CDC-7600 computer)			
Intrinsic FORTRAN functions	*	*	*
Numeric precision	*	*	*
Total Uncertainty	3.7	2.1	5.6

* indicates < 0.00001%.

CONCLUSIONS

We evaluated five algorithms for converting diffuse horizontal and direct normal solar irradiance to global irradiance on tilted surfaces using measurements from monitoring equipment installed at SRRL from 22 July to 4 September 1984. Our analysis indicates the total uncertainty of the study to be ±5.6%. In other words, the difference between the model results and the measurements must exceed this total uncertainty before we can judge the performance of the algorithms.

- The Isotropic method overpredicts irradiance on a north-facing vertical surface by 18.5%. The algorithm performs below or near the total uncertainty for east-, south-, and west-facing vertical surfaces.
- The Temps and Coulson algorithm overpredicts the irradiance for all orientations by 9.5%-46.5%.
- The Klucher algorithm overpredicts irradiance for all orientations from 2.1% (less than the total uncertainty of our analysis) to 29.2%.
- The Hay algorithm performs within measurement accuracy for east-, south-, and west-facing vertical surfaces. It overpredicts irradiance of the north-facing vertical surface by 14.6%. This method achieved the least overall %mbe.
- The Perez algorithm estimates the irradiance for the east-facing orientation within measurement accuracy. It overpredicts irradiance on south- (6.7%), west- (10.6%), and north-facing (18.0%) orientations.

The performance of all algorithms was poorest for the north-facing vertical surface. The average daily total irradiance levels measured on this orientation were between two and three times less than those levels observed for the other orientations.

Because of the limited data available at the time of our study, our results should be considered preliminary and inconclusive. Nevertheless, a fairly clear picture is emerging that indicates deficiencies in the estimates of diffuse sky component radiance.

REFERENCES

Abernethy, R.B., and B. Ringhiser, 1985. *The History and Statistical Development of the New ASME-SAE-AIAA-ISO Measurement Uncertainty Methodology. 20th AIAA/SAE/ASEE Joint Propulsion Conf. (July 1985).* AIAA-85-1403. New York: American Institute of Astronautics and Aeronautics.

Coulson, K.L., 1975. *Solar and Terrestrial Radiation.* New York: Academic Press.

Hay, J.E., and J.A. Davies, 1980. Calculation of the solar radiation incident on an inclined surface. *Proc. 1st Canadian Solar Radiation Data Workshop* (Toronto, Canada, April 1978). Downsview, Canada: Canadian Atmospheric Environment Service, Minister of Supply and Services Canada, pp. 59-72.

Hay, J.E., and D.C. McKay, 1985. Estimating solar irradiance on inclined surfaces: A review and assessment of methodologies. *Int. J. of Solar Energy* 3:203-240.

Hickey, J.R., H.L. Kyle, B.M. Alton, and E.R. Major, 1986. ERB NIMBUS 7 Solar Measurements: 7 Years. *Proc. 6th Conf. on Atmospheric Radiation,* (Williamsburg, VA, May 1986). Boston, MA: American Meteorological Society, pp. 290-293.

Klucher, T.M., 1978. *Evaluation of Models to Predict Insolation on Tilted Surfaces.* NASA TM-78842. Cleveland, Ohio: NASA Lewis.

Kondratyev, K.Ya., 1969. *Radiation in the Atmosphere.* New York: Academic Press.

Liu, B.Y.H., and R.C. Jordan, 1960. The inter-relationship and characteristic distribution of direct, diffuse and total solar radiation. *Solar Energy* 4:1-19.

Perez, R., and R. Stewart, 1984. Real time comparisons of models estimating irradiation on sloping surfaces. *Proc. 1984 Annual Meeting, American Solar Energy Society, Inc.* (Anaheim, CA, June 1984) Boulder, CO: ASES, pp. 645-650.

SERI, 1982. *International Energy Agency Conference on Pyranometer Measurements.* (Boulder, CO, March 1981). SERI/TR-642-1156. Golden, CO: Solar Energy Research Institute.

Temps, R.C., and K.L. Coulson, 1977. Solar radiation incident upon slopes of different orientation. *Solar Energy* 19:179-189.

Passive Solar Journal, 4(2), 211-224 (1987)

Superinsulated Houses in the United Kingdom

John Littler and Paul A. Ruyssevelt
Research in Building Group
Polytechnic of Central London
London NW1 5LS
England

Abstract

This article describes the application of the North American superinsulated house technology to the somewhat milder climes of the south of England. The project is coordinated by the Research in Building Group at the Polytechnic of Central London as part of the European Communities demonstration program in energy conservation.

The project consists of 12 houses, 8 of which will have been continuously monitored for 18 months at the end of the program in June 1987. Initial results are encouraging, with householders experiencing heating bills of less than $45 (£30) for the 1985/1986 heating season. The

houses are extremely comfortable and are free of condensation, which is a common problem with modern housing in the United Kingdom.

INTRODUCTION

The standards of insulation in the United Kingdom (UK) are presently less stringent than those in most other European and Scandinavian countries. Figure 1 illustrates the prevailing standards, as total energy cost per unit of floor area.

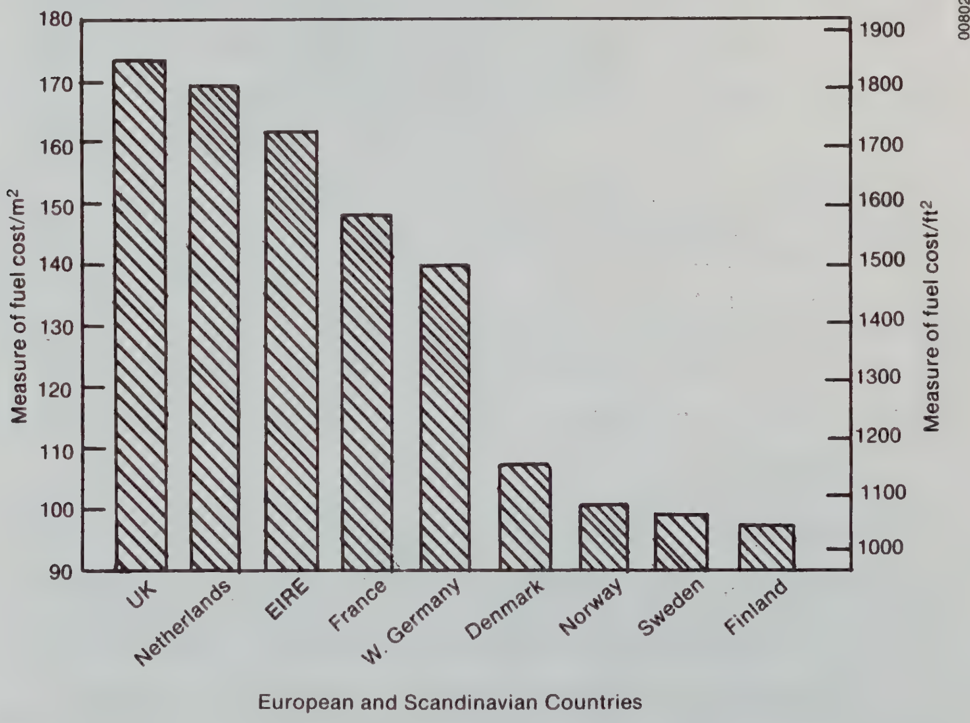


Figure 1. Insulation standards in housing

Costs for space heating in the United Kingdom are typically above \$500 (£350) per year, which is about 5% of the average income after tax. Consequently, a project was undertaken with the following three aims:

1. To demonstrate that cost savings with insulation outweigh the added costs of borrowing the extra capital required for the insulation and its installation;

2. To show that the next stage of development is realistic, in which a distributed heating system and its associated cost are replaced by a single, inexpensive heat source; and
3. To produce evidence that superinsulation increases comfort.

Currently, many demonstration projects in the United Kingdom are investigating the advantages of passive solar gain combined with moderate levels of insulation in housing. However, we are not aware of any monitored houses achieving the same standards of conservation in the United Kingdom as those described here. In addition to studying passive gain and moderate insulation, this demonstration project is designed to show the benefits of superinsulation alone because not all sites are ideally suited for passive solar housing.

This project involved the building of 12 homes, 4 of which were superinsulated, and the other 8 control homes. The houses are located in the new town of Milton Keynes, about 50 miles north of London. The 20-year mean degree-days is 3654°F day (2030°C day). Milton Keynes has been host to many low-energy and solar projects in the past, the latest of which is a development of 1400 houses plus industry and commerce on a site known as the Energy Park. In order to build houses in this development, the planner must have a design that falls below a target of 120 on the Milton Keynes Energy Cost Index (MKECI), which is illustrated in Figure 1. The superinsulated houses score 68 on MKECI.

Each three-bedroom, semidetached house has a total floor area of 810 ft^2 (75 m^2) and an attached garage. The extra cost of the conservation measures and the ventilation system in the superinsulated houses was about $3150 (£2193) per dwelling. This figure includes builders' profit and is based on 1985 prices. Table 1 details actual construction costs.

CONSTRUCTION

The House Frame

Four superinsulated houses (Figure 2) and eight control houses of identical floor plan were built using timber frames imported from Finland. Table 2 shows the U values and total heat loss rates calculated for the skin.

Table 1. Actual Construction Costs

	Cost					
	Superinsulated		Control		Difference	
Item	$	(£)	$	(£)	$	(£)
Timber frame and erection[a]	14,000	(9712)	12,470	(8658)	+1530	(+1054)
Heating and domestic hot water system	1060	(734)	1390	(964)	-350	(-230)
Loft insulation +200 mm	260	(181)	0	(0)	+260	(+181)
Ventilation system	1210	(841)	0	(0)	+1210	(+841)
Under floor insulation	480	(331)	0	(0)	+480	(+331)
Window-frame vents	0		100	(70)	-100	(-70)
Bathroom extract	0		120	(80)	-120	(-80)
Cooker extract	0		170	(120)	-170	(-120)
Superinsulation extra cost	17,010	(11,799)	14,250	(9892)	2740	1907
Plus builders profit @ 15%					3150	(2193)

[a] Difference = +95 mm of wall insulation and triple glazing with one "low-e" coating.

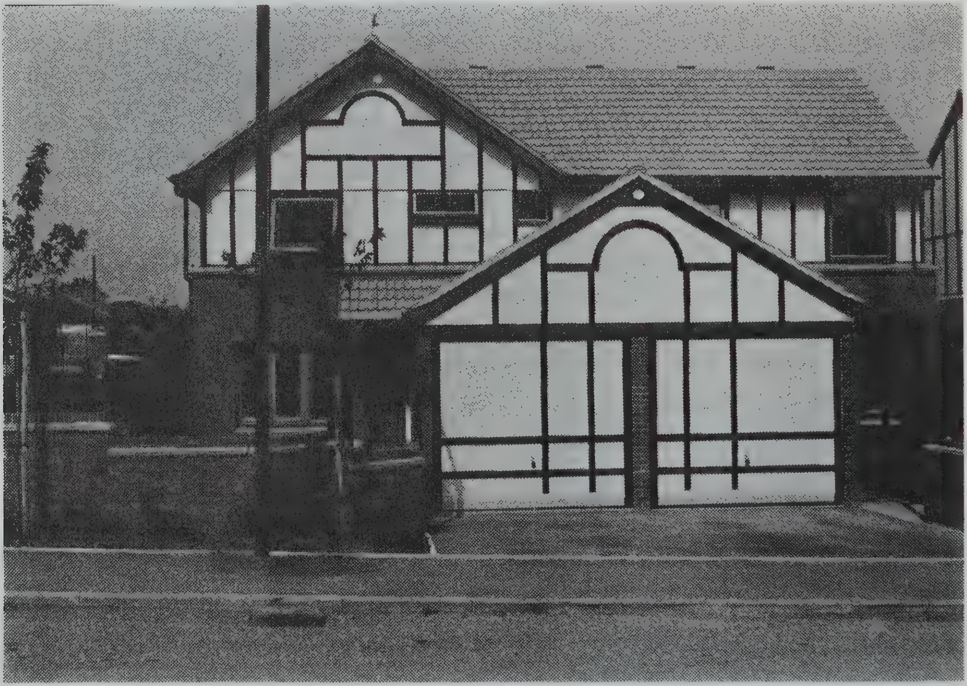


Figure 2. View of superinsulated house

Table 2. Skin Conductance (U) and Total Fabric Heat-Loss Rates (Calculated)

Item	Conductance, U			
	Superinsulated Houses		Control Houses	
	Btu/h ft^2 °F	(W/m^2 K)	Btu/h ft^2 °F	(W/m^{2}K)
Floors	0.035	(0.2)	0.146	(0.83)
Ceilings	0.021	(0.12)	0.062	(0.35)
Walls	0.044	(0.25)	0.071	(0.4)
Windows	0.254	(1.44)	0.85	(4.8)
Glazed doors	0.275	(1.56)	0.85	(4.8)
	Total heat loss rate, UA (excluding ventilation)			
	2360 Btu/°F day (52.0 W/K)		8820 Btu/°F day (194.0 W/K)	

Because the control house walls are timber frame, the U values are somewhat lower than required by 1985 UK Building Regulations. Had the control houses been built strictly according to the regulations, the total heat-loss rate would be approximately 9550 Btu/°F day (210 W/K) rather than 8820 Btu/°F day (194 W/K).

A structural and subframe technique was used for the timber frames, allowing 6 in. (145 mm) of glass fiber in the outer layer separated from an inner thickness of 1.5 in. (40 mm) of insulation by a polythene vapor barrier. Services were factory fitted in the 1.5 in. (40 mm) space in Finland. Figure 3 illustrates a section through the wall.

Currently, no British regulations exist concerning floor insulation, yet comfort and common experience confirm the adverse effects of cold floors. In this project, the floors are insulated with 4-in. (100-mm) extruded polystyrene in 2-in. (50-mm) slabs, as illustrated in Figure 3.

The roof is insulated with 12 in. (300 mm) of glass fiber laid in three separate layers with joints crossing at right angles. Figure 4 shows a detail of the roof insulation and illustrates the means of achieving loft ventilation at the eaves. The eaves ventilators are complemented by a series of ridge vents that allow free passage of air through the loft and help preserve the timber.

008031

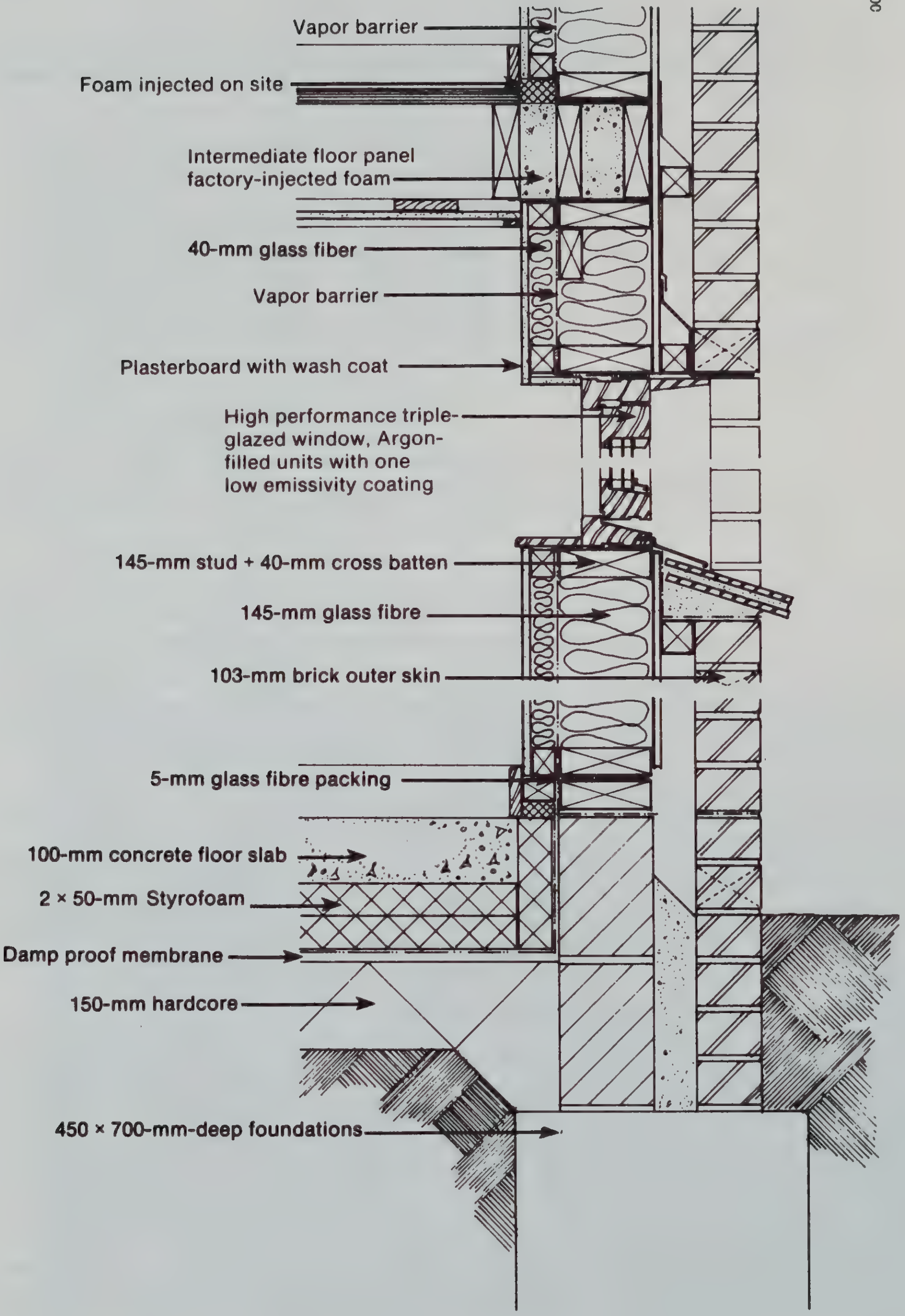

Vapor barrier
Foam injected on site
Intermediate floor panel factory-injected foam
40-mm glass fiber
Vapor barrier
Plasterboard with wash coat
High performance triple-glazed window, Argon-filled units with one low emissivity coating
145-mm stud + 40-mm cross batten
145-mm glass fibre
103-mm brick outer skin
5-mm glass fibre packing
100-mm concrete floor slab
2 × 50-mm Styrofoam
Damp proof membrane
150-mm hardcore
450 × 700-mm-deep foundations

Figure 3. Section through superinsulated wall and floor

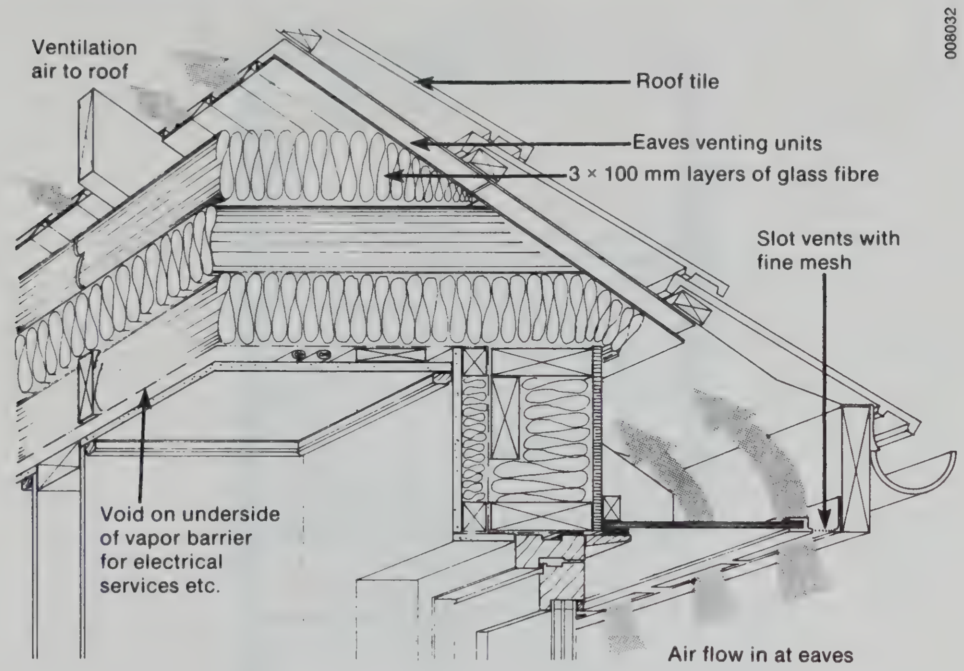

008032
Ventilation air to roof
Roof tile
Eaves venting units
3 × 100 mm layers of glass fibre
Slot vents with fine mesh
Void on underside of vapor barrier for electrical services etc.
Air flow in at eaves

Figure 4. Detail of eaves construction and roof insulation

The architects on this project, Feilden Clegg Design, depart from the norm in the UK by using high-quality Scandinavian timber windows in all their housing schemes. The windows are fitted with factory-installed seals, so the air leakage is minimal. Triple glazing with argon fill in 0.5-in. (12-mm) cavities is improved further by having the innermost pane made of Kappafloat (soft-coat, low-emittance glass from Pilkington, UK).

Like the windows, the doors were glazed and factory fitted to the timber frames. The heavily used front door is protected by a lobby. Figure 5 is a ground-floor plan, and Figure 6 is a plan of the bedroom floor.

The Ventilation System

A Bahco heat-recovery unit is fitted above the stove. The minimal noise generated by this unit is no greater than any other appliance in the kitchen. Stale air is extracted from the other wet areas, in the bathroom upstairs and the toilet downstairs. Fresh air is delivered

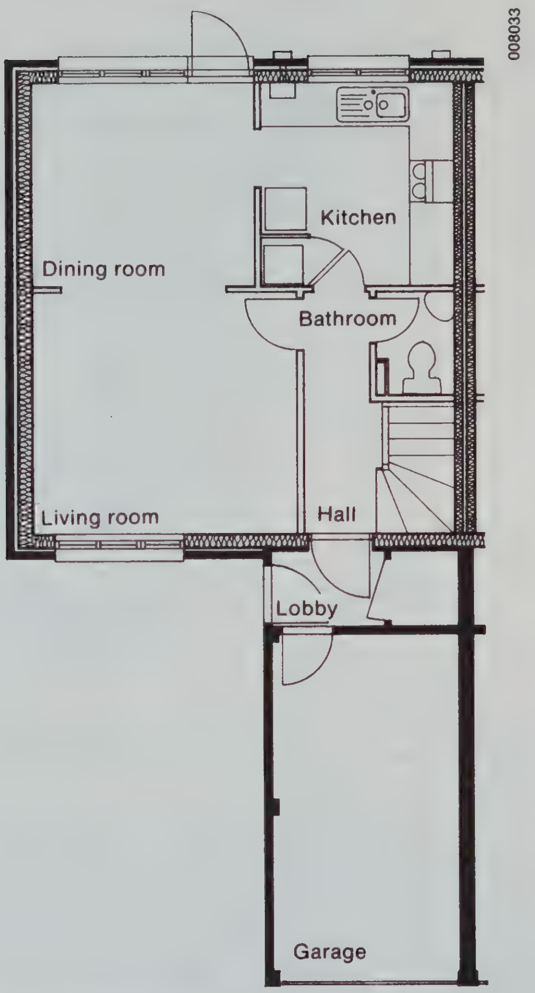


Figure 5. Ground floor plan, 405 ft^2 (37.5 m^2)

to each room via 4-in. (100-mm) diameter steel ducts. To reduce costs and heat loss, all the ducts were fitted in the intermediate floor. Placing the unit in the kitchen rather than in the loft, the typical location, avoids puncturing of the vapor barrier with the numerous ducts. The installed cost of the system was $1210 (£841) at 1985 prices.

Fears have been expressed about fires in heat exchangers above stoves; however, the exchanger in this unit is incombustible, and sensors are provided to cut out the fans should a grease fire occur. A boost mode roughly doubles the rate of extraction via the hood over the cooking area, allowing a clothes drier to be exhausted into the kitchen without the risk of condensation.

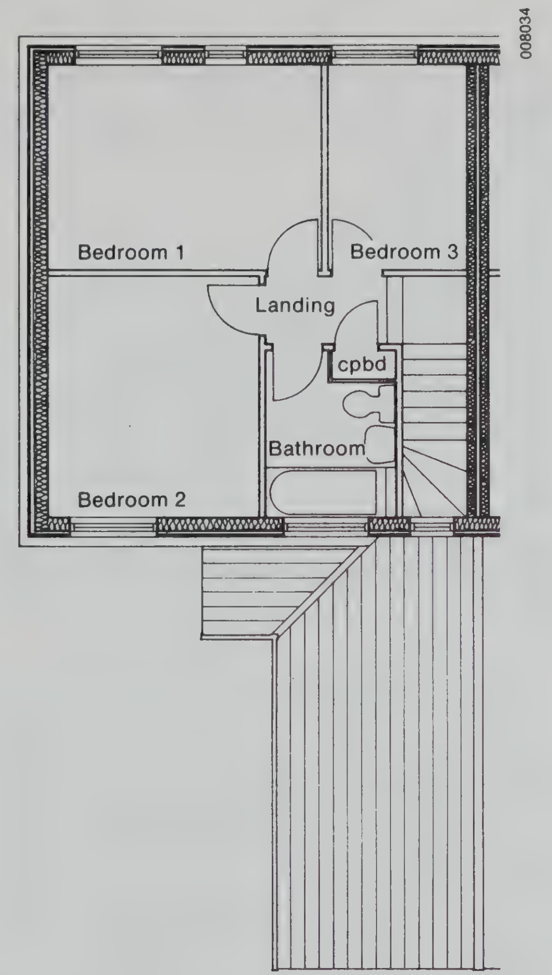


Figure 6. **First-floor plan, 405 ft^2 (37.5 m^2)**

The Heating System

The design heat load of 5125 Btu/h (1.5 kW) for these houses is low and did not warrant the installation of a complete warm air or radiator system. Instead, the ventilation air carries heat to each room using a water-to-air coil in the fresh air stream. This coil is fed from a hot-water storage tank, but the heat could be supplied equally well by a resistance element, with the corresponding savings in capital. The novel gas heater used was not chosen specifically for this project, but rather to evaluate its performance. In practice, a much simpler system would probably improve the overall performance of the house even further. The system installed uses a small gas heater, externally vented and supplied, to maintain a larger than normal hot water tank (180 l) at 180°F (80°C). The tank contains a heat exchanger for domestic hot water and feeds the coil in the fresh air stream directly.

The Monitoring System

One hundred thirty-six channels of data are logged hourly from the four superinsulated houses and four control houses. Sensors are scanned at speeds that vary according to the rate of change in the signal. For example, the voltages from Licor pyranometers are sent to memory every 15 s, and the average is logged on the hour.

One of the superinsulated houses is monitored intensively with a total of 50 channels. The type of data recorded from all the houses is shown in Table 3.

Table 3. Allocation of Monitoring Data Channels

Sensor readings taken in four superinsulated and four control houses

- Living room, hall, and master bedroom temperatures
- Total electric power consumption
- Total gas consumption
- Primary heat supplied to storage tank
- Quantity of hot water drawn off and heat required
- Operation of heating system
- Operation of ventilation system

Additional sensor readings taken in demonstration house

- Temperature readings in all rooms
- Ventilation system temperatures
- Temperatures throughout heating system
- Temperature readings in the ground floor slab and soil (complementary sensors are located in a control house)
- Additional status monitoring of various appliances
- Additional temperature sensors for experimentation

Meteorological sensor readings

- Two external temperatures
- Solar radiation on east and west vertical planes
- Wind speed and direction

RESULTS

Integrity of Construction

Initially, the timber-frame erection process took one day for each semidetached unit, but by the end of the contract, each pair of houses was erected in one day. The roofs, built on the concrete slab prior to the arrival of the wall panels, were set down on the upper story wall panels. The only constructional error resulting in heat loss occurred when a 5-mm layer of glass fiber compressed between the intermediate floor and the wall panels was dislodged in places, allowing minimal air leakage. This problem was virtually unavoidable given the difficulty of maneuvering large panels in high winds.

A thermographic survey carried out on both the superinsulated and control houses revealed the following:

- No missing or misplaced insulation in any walls
- Good joints between panels
- Slight thermal bridging toward the edge of the ground floor, particularly in the control houses
- Limited misplaced insulation in the roof (site error)
- Slight air infiltration around gas boiler flue.

In general, the study showed the houses to be constructed considerably better than the standard UK timber-frame house.

The overall heat-loss coefficient for the superinsulated houses calculated using American Society of Heating, Refrigerating and Air-Conditioning Engineers values for materials is 2364 Btu/°F day (52 W/K), excluding ventilation, and 2955 Btu/°F day (65 W/K) with a background air infiltration rate of 0.2/h. Electric coheating experiments gave values of 3090, 3318, and 3682 Btu/°F day (68, 73, and 81 W/K) for three of the four superinsulated houses. The first two results of 68 and 73 W/K are close to the predicted value given the accuracy of the method. The last figure of 81 W/K is somewhat high because the house was incomplete at the time of the experiment. The rate of background air infiltration also caused a variation in the results.

The breakdown of predicted heat loss by element is shown in Table 4. Heat loss is not being measured separately for each of these elements, but measured data are available for the floors and ventilation.

Table 4. Heat Loss by Constructional Element in Superinsulated House (Calculated)

Element	Area (A)		U value		UA	
	ft^2	m^2	Btu/h ft^2 °F	(W/m^2K)	Btu/h °F	(W/K)
Windows	140	(13)	0.254	(1.44)	850	(18.7)
Walls	780	(72)	0.044	(0.25)	820	(18.0)
Bedroom ceilings	400	(37)	0.021	(0.12)	200	(4.5)
Floor	400	(37)	0.04	(0.2)	340	(7.4)
Doors	20	(2)	0.275	(1.56)	140	(3.1)
Ventilation (0.2 ach)					550	(12.0)
Total					2900	(63.7)

Heat Loss from the Ground-Floor Slab

Figure 7 illustrates the grid of temperature probes in and under the floor of the intensively monitored superinsulated house and one of the control houses. The calculated U value of the floor of the superinsulated house is 0.035 Btu/h °F ft^2 (0.2 W/m^2K) using the 100 mm of extruded polystyrene as an element whose conductivity is well characterized as 0.156 Btu/h °F ft^2 (0.27 W/mK). The experimental value for the multilayer floor determined from temperature measurements over seven months of the heating season was 0.025 Btu/h °F ft^2 (0.14 Wm^2K) for the 172-ft^2 (16-m^2) perimeter area and 0.032 Btu/h °F ft^2 (0.18 Wm^2K) for the 226-ft^2 (21-m^2) central area. These results give a mean U value of 0.028 Btu/h °F ft^2 (0.16 W/m^2K) and a specific heat-loss rate of 272 Btu/°F day (6 W/K). By using the conductivity of concrete derived from this long-term measurement, the U value of the control house floor slab was determined to be 0.168 Btu/h °F ft^2 (0.96 Wm^2K), resulting in a specific heat-loss rate of 1636 Btu/°F day (36 W/K). The value of the soil as an insulator is clearly negligible compared with 4 in. (100 mm) of extruded polystyrene.

Infiltration and Ventilation

Ventilation rates have been measured using a portable gas decay technique. Sulphur hexafluoride is injected at 1 part in 10^9 and its

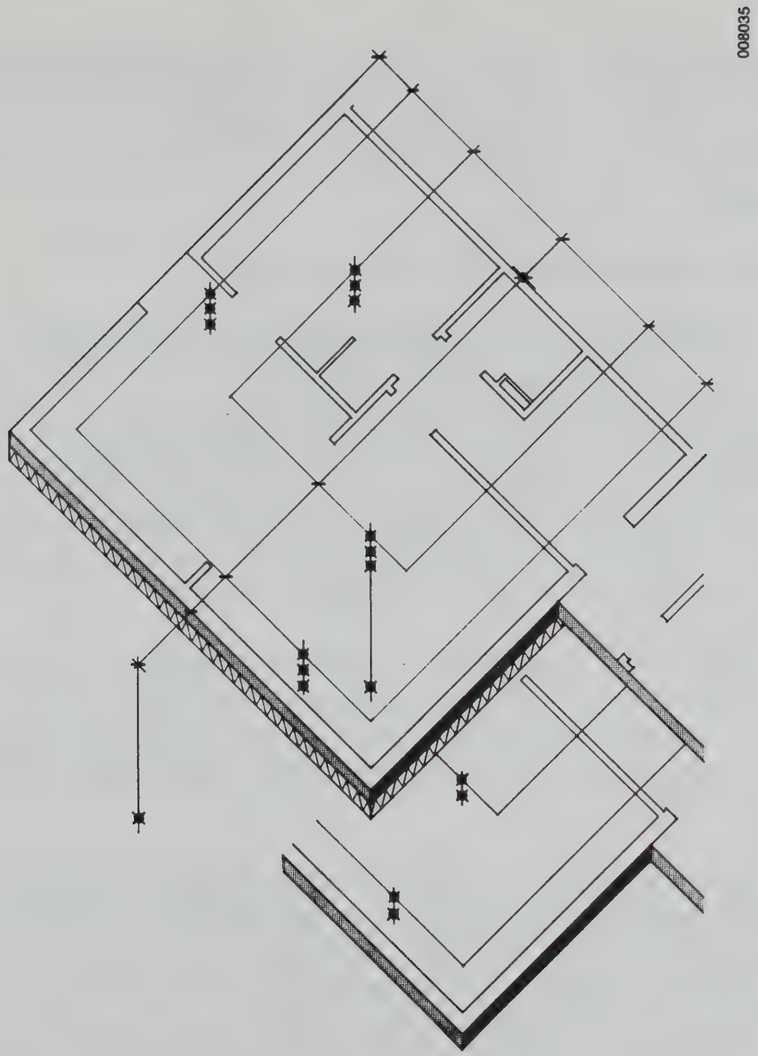


Figure 7. Temperature probes in and under the floor

concentration monitored using a sensitive electron capture detector. The background ventilation rate with the Bahco unit switched off is less than 0.2 air changes per hour (ach). When the fans are in normal mode, the rate increases to 0.9 ach and in boost mode to 1.1 ach.

The airtightness of the main demonstration house was recently tested using a blower door. The result was an air change rate of 1.43 at 50 Pa (0.2 in. water gauge), which was impressive considering that the house had been occupied for 18 months.

The performance of the ventilation system was monitored over the first four months of 1986 and shows heat-recovery efficiencies typically above 75%. The claim that clothes driers could be vented into the house directly without fear of condensation has been validated.

System Performance and Consumer Reaction

In the first four months of 1986, the auxiliary heating requirements of the four superinsulated houses ranged from 900 to 1100 kWh. The heating requirements of the control houses ranged from 2500 to 3500 kWh. Apart from the 60% mean reduction over the control houses the heating requirement of the superinsulated houses is remarkably constant across a range of occupancy patterns. The average temperature over this period for the four superinsulated houses ranges from 66° to 68°F (18.8° to 20.0°C).

Overheating was considered a possible problem in well-insulated lightweight houses. However, experience has shown that during the summer months, the homeowners use natural ventilation, and the peak temperatures are not greater than those that occur in the control houses.

On the rare occasion a speedy warm-up was required in the superinsulated houses, the water-to-air heat exchanger in the ventilation system was slow to respond. Although the throughput of air is automatically boosted in high-demand situations, desired temperatures are not reached as quickly as they are in the control houses with the radiator systems. On reflection, some means of boosting the system with recirculated air, rather than cold air from outside, would have been beneficial. Alternatively, one or two radiant heat sources on each floor would probably be adequate.

In general, the homeowners are very pleased with the superinsulated houses. The slow warm-up from the heating system does not appear to have been a problem because the temperatures in the houses rarely drop significantly, even when the houses are unoccupied over extended periods. The occupants are pleased not only with the low heating bills but particularly with the continuously maintained levels of comfort and the complete elimination of condensation.

Passive Solar Journal, 4(2), 225-229 (1987)

Book Review

The New England Solar Energy Atlas

David Lionel Cook. Orono, Maine: Department of Mechanical Engineering,
University of Maine. 1986. 75 pp. Softbound. $10.00. (Distributed by the
Department of Industrial Cooperation, University of Maine,
109 Boardman Hall, Orono, Maine 04469-0110.)

The New England Solar Energy Atlas offers a convenient source of historical solar radiation data excerpted from the *Solar Radiation Energy Resource Atlas of The United States*. The collection of regional maps and the graphic summaries of the resource data pertinent to the New England area accomplish the author's goal of providing design data in a more compact format than that of the national atlas. The reader would be well advised, however, to consult additional references before attempting to understand the origins of the information and the application of the data summarized in either atlas.

Recognizing the importance to the reader of where the data came from and how to interpret the information presented in the atlas, Cook provides a brief review of solar radiation components, the historical background of the SOLMET/ERSATZ data base, and the generation of the typical meteorological year (TMY) data sets. He also provides the reader with explanations of how to interpret the atlas maps and graphs for general design problems. Cook presents the textual information in a logical order, but I found some of the explanations too brief or misleading.

His discussion of the solar constant is technically correct, but he fails to mention the value (1377 W/m^2) used by the National Oceanic and Atmospheric Administration for rehabilitating the SOLMET measurements and estimating the ERSATZ station values that form the basis of the atlas. It might have been helpful to mention the range of values used in the literature for the solar constant (1353-1377 W/m^2) or the World Meteorological Organization's estimate of uncertainty (1370 ± 6 W/m^2).

In describing the solar components, the author equates the need for direct normal irradiance data with the design of concentrating collectors. Although this application is certainly one use for these data, other uses do exist, including the prediction of the thermal performance of buildings, or the execution of any application where the knowledge of the quality of solar irradiance (diffuse, global) is needed. When referring to the diffuse component as "of secondary importance," Cook underestimates the need for this type of data in daylighting and photovoltaic applications.

Cook's discussion of the 26 SOLMET and 222 ERSATZ stations provides the reader with most of the necessary background to appreciate where and how the data for the atlas were taken. It was not made clear, however, that the data for SOLMET stations include:

- Measured hourly integrated global horizontal irradiance
- Engineering corrected global horizontal irradiance (e.g., observations corrected for known instrumentation errors)
- Standard year irradiance values of global horizontal irradiance (e.g., radiation model estimates used as a quality control check on the measured data and as a means of filling in missing data)
- Estimated hourly integrated direct normal irradiance based on the rehabilitated global horizontal data
- Surface weather observations, including cloud cover, temperature, pressure, wind, and precipitation.

The measured hourly integrated global horizontal irradiance data are quite different from the data from the ERSATZ stations, which have estimates of these quantities based primarily on polynomial regressions developed for cloud-cover observations and the rehabilitated global data for 25 SOLMET control stations. No hourly direct normal estimates were made for the complete 23-year period of record for the ERSATZ stations.

The note under Table II concerning the Central Park, N.Y., SOLMET station is incorrect. Solar radiation data are available for this station for 1 July 1952 to 31 December 1975 from the National Climatic Data Center, Asheville, N.C. The Central Park station was not used as a control in estimating the ERSATZ data because it represents a uniquely urban environment.

Clarification is needed for the generation of the TMY and ERSATZ TMY (ETMY) data sets. Sandia National Laboratories, under contract to the Department of Energy, developed a method for selecting a typical meteorological month by comparing the monthly cumulative distribution functions (CDF) for solar radiation, temperature, and wind with the long-term (23 years) CDF. The collection of typical months was assembled into TMY data sets for the SOLMET stations and into ETMY data sets for the ERSATZ stations. It is important to realize that direct normal solar irradiance estimates for the ERSATZ stations are available only for the ETMY data set. These estimates were made at the time the national atlas was prepared, using a simplified version of the Aerospace direct insolation prediction algorithm. No estimates exist of hourly direct normal irradiance corresponding to the complete 23-year period for the ERSATZ stations.

Cook has conveniently identified sections of the New England atlas that he considers optional reading. These sections add to the background some readers might need to better understand the data. The reader will benefit from Cook's illustrative examples for converting from local standard time to solar time, the discussion of solar geometry, and his review of units for solar radiation. The section describing how to read the contour maps is a welcome addition to the atlas because he uses this format to present most of the information.

The reader of either atlas should be cautioned about the temptation for direct (linear) interpolation between the map contours. These maps were prepared to represent the synoptic scale and do not account for the mesoscale variabilities associated with urban/rural, coastal/inland, or mountain/valley environments.

The New England atlas includes annual time-series plots of daily total direct normal and global horizontal irradiance, the average diurnal profiles of direct normal irradiance, and the cumulative frequency distribution plots from the national atlas. These data provide additional insight into the variability of the solar resources at specific locations, as summarized over the 23-year period of record.

Not mentioned in the New England atlas is the information available on microfiche for each of the 248 stations cited in the national atlas. Four microfiche formats are available. Three formats apply to ERSATZ stations and one to SOLMET stations, as follows:

- Type I—Atlas Tables and Graphs (SOLMET)
- Type II—Solar Atlas Tables (ERSATZ)
- Type III—Typical Year CDF Plots (ERSATZ)
- Type IV—Typical Year Tables (ERSATZ)

Microfiche and paper copies can be ordered from the National Climatic Data Center, Federal Building, Asheville, NC, 28801-2696, telephone (704) 259-0682.

The following references should also be consulted before using either the New England atlas or the national atlas in order to understand the possible limitations of the data summaries:

> *SOLMET Volume 1: User's Manual—Hourly Solar Radiation-Surface Meteorological Observations.* TD-9724. Asheville, NC: National Climatic Data Center, 1977.
>
> *SOLMET Volume 2: Final Report—Hourly Solar Radiation-Surface Meteorological Observations.* TD-9724. Asheville, NC: National Climatic Data Center, 1979.

Typical Meteorological Year, User's Manual. TD-9734. Asheville, NC: National Climatic Data Center, 1981.

Hall, I., R. Prairie, H. Anderson, and E. Boes, *Generation of Typical Meteorological Years for 26 SOLMET Stations.* SAND78-1601. Albuquerque, NM: Sandia National Laboratories, 1978.

Knapp, C., T. Stoffel, and S. Whitaker, *Insolation Data Manual.* SERI/SP-755-789. Golden, CO: Solar Energy Research Institute, 1980. Available from NTIS, Springfield, VA 22161.

Knapp, C., and T. Stoffel, *Direct Normal Solar Radiation Data Manual.* SERI/SP-281-1658. Golden, CO: Solar Energy Research Institute, 1982. Available from NTIS, Springfield, VA 22161.

Solar Radiation Data Directory. SERI/SP-281-1973. Golden, CO: Solar Energy Research Institute, 1983. Available from NTIS, Springfield, VA 22161.

Iqbal, M., *An Introduction to Solar Radiation.* Ontario, Canada: Academic Press Canada, 1983. ISBN 0-12-373752-4.

As Cook states in his introduction, "data for solar engineering is very sparse and often obscure." By producing an atlas for New England, he has helped considerably to provide the solar designer with the best information available at a reasonable cost.

As a postscript, it is worth mentioning that the Solar Energy Research Institute might have the Government Printing Office reprint the atlas. Copies of the first printing originally sold for $18.

Reviewed by Tom Stoffel
Solar Energy Research Institute
Golden, CO 80401

Events

PLEA 88 (Passive and Low Energy Architecture)—"Energy and Buildings for Temperate Climates"
Porto, Portugal, July 27-31, 1988.

This conference will concentrate on the problems of energy-conscious building design in temperate climates, with a special focus on the Mediterranean Basin. Two additional technical events will take place during the same week: a technical exhibition and fair, held in a 15,000 m^2 pavillion, on renewable forms of energy and materials and equipment for low energy use in buildings; and an Iberian section of ISES meeting, which will also contribute toward the promotion of renewables.

Contact PLEA 88 Secretariat
Av. Antunes Guimaraes 102-1., Sala 7
4100 Porto
Portugal

PSA-88 (Passive Solar Architecture)
Bled, Yugoslavia, March 21-25, 1988

This conference on passive solar architecture will emphasize design of institutional, commercial, and multistorey residential buildings. Additional conference activities include a one-day international workshop on advanced passive solar design; a software exhibit; and a guided tour to Ljubljana, the capital of Slovenia.

Contact PSA-88 Secretariat
SLOSE Murnikova 2,
61000 Ljubljana
Yugoslavia

Passive Solar Journal, 4(2), 233-235 (1987)

About the Contributors

Richard E. Bird recently retired as a Senior Scientist in the Resource Assessment and Instrumentation Branch of the Solar Energy Research Institute. He received his Ph.D. in physics from Brigham Young University. His major contributions include research in broadband and spectral solar radiation models, the development of internationally recognized solar spectral standards, instrumentation for atmospheric and spectral measurements, and atmospheric effects on solar cell performance.

Richard L. Crowther was elected a Fellow of the American Institute of Architects in 1983 for applied research in architecture. His completed architectural projects through a period of 50 years are located throughout the United States and Mexico. His architectural and energy conservation concepts and solar and natural energy writings have been widely published in numerous professional journals and books.

Edna Ishai is a Senior Lecturer in the Faculty of Architecture and Town Planning at the Technion-Israel Institute of Technology, Haifa, Israel, and is a practicing designer and consultant in architecture. She has a bachelor's degree in architecture and a doctorate in science from the Technion, and a masters in architecture from the University of Michigan Ann Arbor. Her major field of interest is industrialization of buildings and product design.

John Littler is Chairman of the Research in Building Group at the Polytechnic of Central London, with responsibility for work on air movement, passive solar design, superinsulation, daylighting, building thermal analysis models, and atrium studies.

Eugene Maxwell is a Senior Scientist in the Resource Assessment and Instrumentation Branch of the Solar Energy Research Institute. He received his Ph.D. in resource assessment from Colorado State University in 1975. He has been conducting research on solar radiation models and solar resource assessment for the past several years.

Daryl R. Myers is a Staff Scientist in the Resource Assessment and Instrumentation Branch of the Solar Energy Research Institute. He received a bachelor of science degree in applied mathematics in 1970 from the University of Colorado College of Engineering. Since 1974 he has worked in broadband and spectral solar radiometric instrumentation, metrology, and software. He has participated in national and international radiometer comparisons.

Peter Pollock is a planner in the Department of Community Planning and Development, City of Boulder, Colo. From 1981 to 1986 he was responsible for the implementation of Boulder's solar access ordinance. He is now Boulder's historic preservation planner. Prior to working at the City of Boulder he was staff urban planner at the Solar Energy Research Institute in Golden, Colo., where he worked for the Community and Consumer Branch on issues related to solar energy and land use planning. Mr. Pollock received a master of landscape architecture degree from the University of California at Berkeley in 1978.

Paul Ruyssevelt is an architect specializing in low energy buildings. For the last 6 years he has carried out a series of research and demonstration projects at the Polytechnic of Central London. He is director of the Energy Monitoring Company, a firm specializing in energy monitoring and analysis.

Richard Schoen is a Professor in the UCLA Graduate School of Architecture and Urban Planning and an architect and planner in private practice. He was elected a Fellow of the American Institute of Architects in 1983. He specializes in innovation and change in the building industry and energy conserving solar design in architecture.

Thomas L. Stoffel is a Staff Scientist in the Resource Assessment and Instrumentation Branch of the Solar Energy Research Institute. He is responsible for the development and operation of the Solar Radiation Research Laboratory where the various broadband solar radiation components are monitored. He received a bachelor of science degree in aerospace engineering in 1970 from the University of Utah. He has conducted research in solar radiation measurements and modeling and helped produce several publications summarizing the national solar radiation data archives.

AMERICAN SOLAR ENERGY SOCIETY

Susan M. Burley, Executive Director
2400 Central Ave., Unit B1
Boulder, Colorado 80301

BOARD OF DIRECTORS

Bruce D. Hunn, Chair*
University of Texas
Austin, Texas

John S. Reynolds, Vice-Chair*
University of Oregon
Eugene, Oregon

William A. Beckman
University of Wisconsin
Madison, Wisconsin

Karl W. Boer
University of Delaware
Newark, Delaware

Francis de Winter*
Altas Corporation
Santa Cruz, California

Fred S. Dubin
Dubin-Bloome Associates
New York, New York

Joe Farber, Ex-Officio
Newport Beach, California

Gary J. Jones
Sandia National Laboratory
Albuquerque, New Mexico

Robert W. Jones
Los Alamos National Laboratory
Los Alamos, New Mexico

Harry Gordon, Secretary*
Burt Hill Kosar
Rittlemann Associates
Washington, D.C.

Marvin Van Der Pol, Treasurer*
Solar Energy Research Institute
Golden, Colorado

Edward Lumsdaine
University of Michigan
Dearborn, Michigan

Pamm McFadden
Elements Design Group
Boulder, Colorado

Frederick H. Morse
U.S. Department of Energy
Washington, D.C.

Mike Nicklas
Innovative Design
Raleigh, North Carolina

Paul Notari*
Solar Energy Research Institute
Golden, Colorado

Blaine F. Parker
University of Kentucky
Lexington, Kentucky

Bruce Wilcox
Berkeley Solar Group
Berkeley, California

Roland Winston
University of Chicago
Chicago, Illinois

*executive committee member

PASSIVE ARCHITECTURE AND CONSTRUCTION DIVISION

Susan M. Burley, Acting Secretary
2400 Central Ave., Unit B1
Boulder, Colorado 80301

BOARD OF DIRECTORS

Pamm McFadden, Chair
Elements Design Group
Boulder, Colorado

Gary Bailey
Innovative Design
Raleigh, North Carolina

Cris Benton
University of California
Berkeley, California

Polly Cooper
San Luis Obispo Solar Group
San Margarita, California

Jim Brown, Vice-Chair
Spring Valley, California

John Duffy
University of Lowell
Lowell, Massachusetts

John Lu
Tennessee Valley Authority
Chattanooga, Tennessee

Alex Wilson
A.T. Wilson Associates
Brattleboro, Vermont

Join the

American Solar Energy Society

Help yourself while you help the cause of Solar Energy.

We invite you to become a member of ASES and join other solar professionals united to advance the cause of U.S. energy independence by adoption of solar energy technologies.

Here are some of the services you will come to enjoy as an ASES member:

- Regular forums for the exchange of technical ideas between professional collegues.
- ***Advances in Solar Energy,*** a compendium of the latest R&D developments in solar energy, authored by select ASES members and published annually by the Society for distribution worldwide.
- Two major technical conferences each year (with published proceedings) presented especially for ASES members and offered to them at special reduced prices.
- A quarterly ***Passive Solar Journal*** in which ASES members may publish their ideas and keep abreast of state-of-the-art developments in this field.
- A quarterly Newsletter with a special technical feature in each issue.
- A wide variety of technical publications offered to ASES members at special reduced prices.
- Special committees and councils providing ASES members the means to voice their views and collectively establish positions on given issues related to solar energy.

ASES needs your support. With the world's diminishing attention to renewable energy development, it is more important than ever that our nation's number one professional solar society remain strong. We can make great strides with your help. Show your commitment and join ASES today. Simply fill in the application below and submit it to the **American Solar Energy Society;** 2400 Central Ave., Unit B1; Boulder, CO 80301. For additional information call (303) 443-3130.

ASES Membership Application

Name ____________________

Title ____________________

Company (if applicable) ____________________

Address ____________________

____

Signature:

____

Please register me as a:

☐ Full Member ASES only ($50)

☐ ASES + ISES* member ($85)

☐ Full member and subscription to *Passive Solar Journal* ($75)

☐ Check enclosed (payable to ASES)

☐ Visa ☐ Mastercard ☐ AE

No. ____________ Exp. Date ________

*International Solar Energy Society — ASES international affiliate. (Dues include subscription to ***Solar Energy Journal.***)

547 76

INSTRUCTIONS TO AUTHORS

Manuscripts proposed for publication are welcome. Manuscripts also will be invited. Manuscripts must be original and unpublished, although previously published data will be permitted. News items are not accepted; book reviews and opinion pieces are encouraged.

Although this is the official journal of the Passive Architecture and Construction Division, American Solar Energy Society, Inc. (ASES), manuscripts are accepted from solar researchers and professionals throughout the world. Authors do not need to be members of ASES.

Manuscripts must be written in English and typed double spaced on one side of 8½ x 11 paper with ample margins. References should be cited by author and date in the text, not numerically [i.e.; "as stated in Smith (1985)..." not "as stated in ref. (1)..."]. Illustrations must be provided, preferably original artwork. Original photos should be provided, preferably 8 x 10 black and white glossy prints. Both English and SI units should be provided in the text, figures, and tables, with the units of the original research cited first and the equivalents in parentheses.

All pages should be numbered consecutively. The general format of the manuscript should be as follows: title of article, names and addresses of authors, abstract (up to 150 words), and text with subdivisions (introduction, summary, etc., acknowledgments, appendices, references, notes), and figures and tables with captions. Manuscripts should be prepared according to the Style Manual of the American Institute of Physics, 335 East 45th Street, New York, NY 10017.

Reprints are available in quantities of 100 and multiples thereof. For orders of 100 or more reprints, 20 free copies are provided. A reprint order form will be sent to the senior author with the final approved copy.

Manuscripts should be sent to Robert W. Jones, Los Alamos National Laboratory, Mail Stop J577, Los Alamos, NM 87545.

Passive Solar Journal

Volume 4, Number 2, 1987

Contents

Opinion

On Energy, Vernacular Architecture, and the Education of Third World Architects in the West 123
R. Schoen

Articles

Architectural Integration of Solar Systems for Domestic Water Heating 129
E. Ishai

Human Migration in Solar Homes for Seasonal Comfort and Energy Conservation 143
R. Crowther

Solar Access in Boulder, Colorado 171
P. Pollock

Solar Irradiance on Vertical Surfaces 187
T. Stoffel, E. Maxwell, R. Bird, and D. Myers

Superinsulated Houses in the United Kingdom 211
J. Littler and P. Ruyssevelt

Book Review

New England Solar Energy Atlas 225
T. Stoffel

Events 231

About the Contributors 233

42067